

VISIT...

LANZAROTE
Caliente.COM

SECTION 21

INDUSTRIAL AND COMMERCIAL APPLICATIONS OF ELECTRIC POWER

Hesham Shaalan

Associate Professor of Electrical Engineering, U.S. Merchant Marine Academy, Kings Point, NY

CONTENTS

21.1	INTRODUCTION	21-2
21.1.1	Links between Competitive Advantage, Efficiency Improvement, and Environmental Compliance	21-2
21.1.2	Environmental Compliance	21-3
21.2	TRENDS IN BUSINESS AND INDUSTRY ENERGY USE	21-5
21.2.1	Impact of Deregulation	21-5
21.2.2	Role of the Energy Service Company	21-5
21.2.3	Retail Power-Supply Options	21-5
21.3	ELECTRICITY IN AGRICULTURE	21-6
21.3.1	Energy Use in Agriculture	21-6
21.3.2	Technology Innovation	21-6
21.3.3	Automation	21-7
21.3.4	Farm Structures	21-7
21.3.5	Plant Production	21-8
21.3.6	Materials Handling	21-9
21.3.7	Maintenance	21-10
21.4	THE FOOD INDUSTRY	21-11
21.5	THE TEXTILE INDUSTRY	21-12
21.6	THE PETROLEUM INDUSTRY	21-12
21.6.1	Oil Refineries	21-13
21.6.2	Electric Motors	21-14
21.6.3	Emergency Power Supply	21-15
21.6.4	Oil-Well Pumping	21-15
21.6.5	Gas-Processing Plants	21-17
21.6.6	Oil Pipelines	21-17
21.7	THE STEEL INDUSTRY	21-19
21.8	THE CHEMICAL INDUSTRY	21-23
21.8.1	Industrial Gases	21-23
21.8.2	Industrial Inorganic Chemicals	21-23
21.8.3	Manufactured Fibers	21-24
21.9	THE PULP-AND-PAPER INDUSTRY	21-24
21.9.1	Industry Organization	21-24
21.9.2	Pulp Mills	21-24
21.9.3	Paper and Paperboard Mills	21-24
21.9.4	Power Distribution System	21-25
21.10	DISTRIBUTED GENERATION	21-25
21.10.1	Why Distributed Generation Is Used	21-25
21.10.2	Distributed-Generation Technologies	21-26

Most of the original material in this Section was developed by engineers at Resource Dynamics Corporation, Vienna, VA.

21-2 SECTION TWENTY-ONE

21.11	ELECTRIC MELTING	21-28
21.11.1	Process Overview	21-28
21.11.2	Melting Pots	21-29
21.11.3	Arc Furnaces	21-30
21.11.4	Induction Furnaces	21-34
21.11.5	Resistance Furnaces	21-36
21.12	ELECTRIC HEATING	21-37
21.12.1	Principles of Heating	21-37
21.12.2	Methods of Electric Heating	21-41
21.12.3	Electric Heating Equipment	21-42
21.13	ELECTROMAGNETIC INDUCTION	21-48
21.14	ELECTRIC WELDING	21-50
21.14.1	Resistance Welding	21-50
21.14.2	Arc Welding	21-51
21.14.3	Induction Welding	21-56
21.14.4	Electron-Beam Welding	21-56
21.14.5	Electroslag and Plasma Welding	21-57
21.14.6	Pressure Welding	21-57
21.15	AIR CONDITIONING AND REFRIGERATION	21-58
21.15.1	Air Conditioning	21-58
21.15.2	Refrigeration	21-68
	BIBLIOGRAPHY	21-75

21.1 INTRODUCTION

21.1.1 Links between Competitive Advantage, Efficiency Improvement, and Environmental Compliance

Since the last edition of this handbook, a newly competitive environment is emerging in the industrial and commercial applications of electric power. While the areas of improving energy efficiency and meeting stricter environmental regulations is still a concern to business and industry, the need to maintain a competitive edge in an increasingly global economy is having a definite impact on energy-related decisions. Technology investments are still being made in process and business enhancements, but the driving force is business economics. Producing goods and delivering services in a way that is “cheaper, better, and faster” is the goal of most competitive organizations. Technologies at the forefront of improving business operations include sophisticated information and communications systems, new sensors and control systems, and constantly improving electrotechnologies. The success of electrical engineering today will depend to a great degree on the extent to which the engineer understands this technological changes, and participates in the business decision making of the company. Nevertheless, the ultimate objective of any successful business is still to improve performance while cutting costs.

Sensors. From an electrical engineering perspective, sensors are an essential element in the operation and control of a manufacturing or other electricity-driven process. Sensors include all devices that respond to a physical, chemical, or biological stimulus and transmit a resulting impulse for measurement or control. Simple devices include electrochemical sensors that determine ionic or molecular concentration, potentiometric sensors that measure the potential difference between two electrodes, and amperometric sensors such as the Clark cell for measuring oxygen in some fluids

(see Sec. 24 for more details). In all cases, the sensor typically responds to a change in condition, and converts the measured variable into an electric signal.

New advances in sensor technology encompass on-line machine diagnostics, remote and noninvasive detection, and improved durability in hostile environments. Sensors are used in industrial plants and mills to control process flows, assembly-line speeds, chemical concentration levels, and many other variables. A typical application of sensors is in industrial flexible manufacturing systems, assemblies of one or more machine tools and workpiece-handling devices, inspection sensors, and part-washing equipment and/or material storage equipment, all operating in a coordinated manner under the control of a central or distributed computer. A flexible manufacturing system is employed to process a variety of finished parts (see Fig. 21-1). Commercial building facility management systems include sensors for input data, remote-terminal units, the central processor, and human-machine interface devices. Functions typically go far beyond energy management, including not only heating, ventilation, and air conditioning (HVAC), but also fire management, security, and access control.

Information and Communications Systems. The information and communications systems in a plant or facility consist of collecting hardware, software, and input/output devices and connecting wire or cable that transmits voice and data, and then processing these data into information and knowledge for decision-making purposes. Improved communications systems are being developed based on high-speed data transfer and expanded application of voice recognition interface. This is the basis for emerging smart information systems that will take full advantage of language translation, natural-language processing, artificial intelligence, storage and processing of only useful data, and interactive computer-based training.

Electrotechnologies. For the electrical engineer, the technologies that use electricity to manufacture or transform a product are of special interest—collectively, these technologies are known as *electrotechnologies*. The industrial-commercial market continues to represent significant opportunities for electrotechnologies, ranging from process heating to metal heating, cutting, and welding. In most electrotechnologies, electromagnetic, electrochemical, and/or electrothermal effects are central parts of the process. Examples of these technologies include induction heating and melting; plasma processing; infrared, microwave, and radio-frequency processing; freeze concentration; and electroseparation. Some of these technologies, such as infrared heating, also have natural-gas-fired alternatives.

A broad set of electrotechnologies includes electric motors, used in the commercial and industrial sectors to drive pumps, fans, and compressors for a wide range of applications. These applications include HVAC applications, fluid processing, compressors to drive freeze concentration, and membrane separation. In the area of materials processing, motors furnish the power for cutting, grinding, and crushing. Finally, the raw materials and manufactured products are moved around the factory floor by motors driving conveyors, cranes, elevators, and robots.

21.1.2 Environmental Compliance

The environmental impact of the industrial and commercial applications of electric power has also rapidly become a primary concern in many industry sectors. Environmental concerns, many heightened by more stringent laws and regulations, are widespread, including such problems as the release of volatile organic compounds (VOCs) during solvent use for example, in industrial painting and curing and disposal of oil-water emulsions, toxic wastes, and other industrial effluents. Mitigation of these problems is typically addressed with the “TR3 approach”—treat, reduce, reuse, or recycle. For example, the generation of VOC emissions can be reduced (or eliminated) with the use of water-based paints or powder coatings combined with infrared drying. A parallel treatment option would include the use of solvent recovery heat pumps, or perhaps freeze concentration to separate VOCs from wastewater.

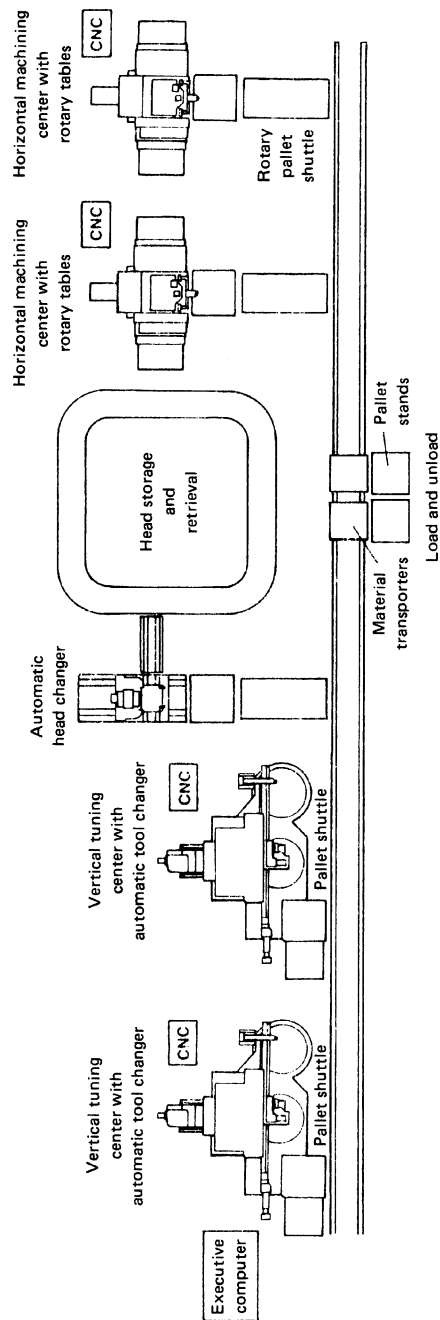


FIGURE 21-1 Schematic illustration of a flexible manufacturing system.

21.2 TRENDS IN BUSINESS AND INDUSTRY ENERGY USE

21.2.1 Impact of Deregulation

By 1900, electric utilities produced approximately two-fifths of the electricity in the United States. The balance of power was supplied by business and industry which generated their own electricity. As larger and more efficient generators and more transmission lines were installed by the electricity industry, costs came down and the associated increase in convenience prompted most customers to concentrate on their core business operations and purchase electricity from the utilities. As originally configured, the electric power industry was based on a central source of power supplied by efficient, low-cost utility generation, transmission, and distribution. Utilities were granted exclusive franchise areas in which to operate, and along with this exclusivity came the obligation to serve all consumers within that territory, and, in most cases, state regulation of privately owned electric utilities in the early 1900s. States typically regulated utility rates, financing, and service, and established utility accounting systems.

The U.S. electric power industry today is in the process of restructuring, which began with the introduction of federal deregulation policies starting with the passage of the Public Utility Regulatory Policies Act (PURPA) of 1978. PURPA was initially positioned as a way to encourage the development and use of alternative fuel resources in the industry. The important long-term effect was the introduction of some level of competition by providing new participants with a gateway to electric utility markets. The key elements of PURPA were the requirements for public utilities to purchase available power from qualified cogenerators and small power producers at rates that were less than or equal to the utility's avoided costs, and provide backup service to cogenerators and small power producers at nondiscriminatory and reasonable rates. In addition, the nonutility generators were exempted from various state and federal regulations. The entrance of a new group of suppliers demonstrated that cogenerators and small power producers represented a viable source for new supply of energy and power services.

The Energy Policy Act expanded markets further in 1992, and in 1996, the Federal Energy Regulatory Commission (FERC) issued rules for implementing open access to the transmission network and for utilities to recover the costs associated with transmission lines and other plant and equipment investments that may be "stranded" as markets become more competitive. Today, the state public utility commissions are actively studying retail competition, and some have already introduced pilot programs or have drawn up plans for restructuring. Newly formed entities, such as power marketers, brokers, and independent system operators, are emerging on the scene. The electric utility companies are being merged and acquired, promising a much different power supply picture in the future.

21.2.2 Role of the Energy Service Company

As the electric utility market has slowly begun to entertain competition, a new kind of business has emerged: the energy service company. The energy service company (ESCO) may be independent, or may be a subsidiary of an electric or gas utility company, and it typically develops, installs, and finances projects designed to improve the energy efficiency and lower operating and maintenance costs for commercial and industrial facilities. ESCOs generally assume the technical and performance risk associated with a specific project, and often act as the project developer and manager. These companies not only install and maintain the energy equipment but also measure, monitor, and verify the project's energy savings. All services provided by the ESCO are usually bundled into the project's cost and are repaid through the savings generated. Projects undertaken include high-efficiency lighting, high-efficiency heating and air conditioning, efficient motors and variable-speed drives, and centralized energy management systems. ESCOs frequently work on a performance-based contracting basis, and often the company's payments are directly linked to the amount of energy that is actually saved.

21.2.3 Retail Power-Supply Options

The ongoing transformation and ever-increasing competitive nature of the electric industry has greatly enlarged the scope and complexity of how electricity will be delivered to the customer. A broad range of power technology options are available and emerging, including fuel cells, turbines, microturbines,

reciprocating engines, and a range of renewable technologies (e.g., photovoltaic and wind). Both economics and reliability are also factors being considered in the development and implementation of these technologies. Many of these technologies are “distributed,” meaning that they are typically sited close to the customer load and are generally smaller in size than the megawatt-sized utility units. Technologies such as solid oxide fuel cells offer a combination of performance and flexibility which makes them an ideal supply resource that helps address regulatory, environmental, and competitive challenges in delivering essential power and energy services. By converting fuel energy directly into electricity, fuel cells provide a clean and strategically economical resource. Microturbines are also getting a lot of attention, and consist of a compressor, combustor, turbine, and generator. This technology is derived from aircraft auxiliary power systems and diesel engine turbochargers. A number of companies are currently field-testing demonstration units, and commercial deliveries started in 1999.

Some deregulation measures did not succeed as originally planned. For example, California’s 1996 law deregulating the electricity market, once hailed as a model for others:

- Forced utilities to sell off much of their generating capacity
- Prohibited them from signing long-term contracts to buy supplies
- Barred increases in consumer rates until 2002

People inside and outside of the state of California wonder how such problems could happen in their state, the home of Hollywood and Silicon Valley. Even though it’s a complicated issue, it mostly results from geography—the state’s population and businesses (especially power-draining high-tech industries) have grown by leaps and bounds over the past decade, while no new power generation plants have been built in the state over the past decade.

Additionally, power can’t be stored up and used at a later time. Supply must equal or exceed demand at the very instant that the demand is there. Due to California’s lack of power generation facilities, California is obtaining power from across the Western United States and less-than-adequate rainfall in the Pacific Northwest has resulted in less power being available from the hydroelectric plants of the Northwest.

21.3 *ELECTRICITY IN AGRICULTURE*

There were 1.9 million U.S. farms in 1997, compared to 5.4 million farms in 1950. Farm output has increased steadily since the mid-1980s, reflecting almost universal use of automation and improved chemical fertilizers. Food products and fiber are the primary outputs of the agricultural sector.

Increased global economic growth had driven increased demand for food and fiber worldwide. The U.S. comparative advantage in agricultural production and transportation has allowed it to capture an increasing share of the growing global demand. In 1996, U.S. agricultural exports reached \$60 billion, and in 1997 exports were \$57 billion and farm prices were firm. Exports slipped to \$55 billion in 1998 as recession hit Asia and expanded production around the world has lowered crop prices.

21.3.1 **Energy Use in Agriculture**

Electricity consumption in the agricultural sector has been decreasing, reflecting farm consolidation and efficiency improvement.

21.3.2 **Technology Innovation**

Increased automation (discussed below) controlled by increasingly sophisticated and lower-cost computer systems has helped improve farming operations across the board. Introduction of advanced technology, such as the written-pole motor, promises improved electric operations to farmers. This motor helps farmers meet the challenge of serving irrigation loads in remote areas. Typically, any irrigation load greater than 15 hp can be served only by a 3-phase motor. Most irrigation sites,

however, are several miles from the nearest 3-phase service, and it is seldom economically feasible to extend service to this distance. Solutions to the problem include the use of a phase converter (discussed in Sec. 21.3.8) to create 3-phase power, or installation of gasoline or diesel engines. These solutions can result in poor power quality and can be expensive and time consuming.

A new type of motor has been developed that is slow-starting and can provide up to 60 hp with a single-phase power supply. In addition, this motor can ride through brief power outages. This new type of motor is designed with high-starting torque, and contains magnetic poles which are continuously and instantaneously written on a magnetic layer in the rotor by an exciter pole in the stator. The magnetic poles can be written to a different spot on the rotor during each revolution whenever the rotor speed changes, keeping the pole pattern constant. They are held in the same pattern when the motor reaches full speed. This variation of the poles during start-up gives the motor its slow-starting, high-torque characteristics. A squirrel-cage winding in the motor also adds induction torque in starting.

This slow-starting capability of the motor, combined with the high-starting torque, offers some benefits to the user. The power quality impact on other customers on the line is limited, and the motor pulls only about 2 times the full load current on start-up, compared to a usual draw of 6 times full load current with most motors.

21.3.3 Automation

Larger-scale farming has adopted automation as standard practice. Solid-state electronic devices are used to control livestock feeding by triggering food-release mechanisms at established intervals; phototransistors are used to thin crops by scanning planted rows with precision and at high speed; electronic sensors are also used on farming machinery to monitor shaft speeds, materials flow, and other parameters.

Planting and harvesting machines are equipped with electronic monitoring devices indicating information such as shaft speeds, material flow rates, temperatures, and seeding malfunctions. Reed switches or hinged-plate switches are used to flash light signals or actuate buzzers and horns, and miniature electrical generators, the output of which is proportional to the speed, indicate shaft revolutions per minute relative to a desired value. This information is displayed on a console within the combine cab, or on the tractor.

Electronic crop thinners, using a phototransistor scanning system for each crop row, have resulted in higher vegetable crop yields than is possible with hand thinning, since earlier thinning and a more uniform plant population are possible. Other uses of electronics include automatic temperature and humidity controls for crop drying and storage, and automated surface sprinkler systems such as the solid-set, permanent-overhead, and center-pivot type (utilizing control consoles, operating through buried cables, microwave channels, VHF radio, and pressure and temperature control switches) to provide round-the-clock irrigation control. Overriding time controls provide cooling when predetermined temperatures are reached.

Livestock-feeding systems use electronic controls for time-interval feeding of individual animals based on current production level, weight, age, etc. A transmitter at the feed station sends a signal to a transponder unit on the animal, which upon activation switches on a relay controlling the feed unit. Automatic data recording can be accomplished for individual animals by means of a special neck band, thus enabling rapid and detailed collection of data which, aided by a computer, facilitates efficient management of larger enterprises. Electric motor drives for farm tractors are possible in the near future.

21.3.4 Farm Structures

Water Systems. Water requirements for the farm household and farm enterprises, excluding irrigation, are frequently supplied by a single well. The water-supply equipment is usually an automatic hydropneumatic or air system having pumping capacity of 300 to 600 gal/h and using a $\frac{1}{4}$ - to 1-hp motor, depending on the total head in feet and the rate of pumping. Home water requirements average 50 gal/(person)(day). In addition, livestock requirements must be added: each horse, steer, or dry cow, 12 gal; each milk cow, 35 gal for drinking and washing equipment; each hog, 3 gal; each sheep, 2 gal; each 100 chickens, 8 gal. For yard fixtures, each $\frac{3}{4}$ -in hose outlet requires 300 gal/h.

Where the source of supply is not more than 22 ft below the pump, a shallow-well system can be used. A jet-centrifugal pump has a practical lift limit of 80 to 100 ft, and piston-type pumps can go as deep as 800 ft with a suction lift below cylinder of 22 ft. This type is placed directly over the well and is generally recommended where pumping depths exceed 80 ft. Automatic pressure switches are usually set to start the pump when the pressure falls to 20 lb and stop it when 40 lb has been obtained. The energy requirement per 1000 gal of water pumped rarely exceeds 2 kWh.

Heating Systems. Electrical heating of farmstead structures is generally confined to milk houses, individual pen-type areas for young livestock, and poultry brooders. Electric heating in the milk house is ideal, as it is odorless, is conveniently controlled, and meets the high sanitary standards required. The milk-house temperature should not exceed 40°F. Several types of heaters have been successfully used: (1) the forced-air circulating type requiring 1500 to 3000 W; (2) batteries of 250-W infrared heat lamps directed toward working areas and water pipes; and (3) heat-pump systems, which utilize the heat removed in cooling the milk. In this type the ice-bank refrigeration system (either bulk or immersion coolers) extracts heat from the water in building up the ice, the heat thus being available for the milk house. Electricity used in this indirect manner produces about three times as much heat as it would if directly used in a resistance heater. Only coolers with 1/2-hp or larger motors are recommended for this application.

In the colder regions, the milk house must be insulated for the most economical cost of installation and operation. In these areas an electrically heated milk house needs at least a 1500-W heater serviced by a 230-V line. Thermostats are usually attached to the heater unit, and operating consumption ranges from 1000 to 3000 kWh a season.

The need for infrared heat lamps during the first week of hog farrowing and sheep lambing has been proved. A 250-W lamp will heat an area 24 in in diameter when 3 ft above the floor. The lamps should be positioned at least 6 in above animals and at least 30 in above the floor when bedding is used.

Ventilation Systems. Electrically powered mechanical ventilation of livestock structures provides low-cost positive control for the removal of excess animal body heat, objectionable odors, and condensation, and for temperature and humidity control. A full-grown cow will give off 3000 Btu/h of body heat; 1000 chickens, about 800 Btu/h. Accurately controlled tests with dairy cows at the University of Missouri showed that temperatures above 75°F and relative humidities over 75% resulted in sharp declines in milk production and body weight.

In general, summer ventilation should maintain inside temperatures equal to or below the outside temperature, while in winter the reverse is true. Thermostatically controlled motor-driven fans are installed as required, with adequate fresh-air intakes to prevent excessive energy costs. Two-speed fans, chosen to move the maximum air volumes required for various livestock, will permit airflow to be reduced in cold weather. Fan motors range from 1/20 to 1/2 hp and will consume 250 kWh/year and up, depending on usage. One kilowatthour of electricity will move about 1 million ft³ of air.

21.3.5 Plant Production

Irrigation Pumping. More electrical energy is used for irrigation pumping than for any other field operation. Proper design of an irrigating system will depend on the following factors: (1) the acreage and kind of crop to be irrigated; (2) the amount of water that must be supplied; (3) the amount of underground water available; and (4) the depth at which it is found.

Except where the water requirements are small and the depth to water great, plunger pumps are rarely used. The more common type is the centrifugal turbine pump, but where the lift is not more than 15 ft, the horizontal centrifugal pump is also used. The bowl of the turbine pump should be set below any expected drawdown in the well, and this will depend on the porosity of the surrounding strata as well as the rate of pumping.

Vertical turbine pumps require vertical motors with either solid or hollow shafts and thrust bearings capable of carrying the pump load. Horizontal pumps should be connected to their motors through flexible couplings to avoid the use of belts. With average allowance for evaporation, irrigating an acre 1 ft deep requires 340,000 gal. The soil can be wet to a depth of 4 ft by using 4 to 6 in

of water. From 10 to 20 in is required to produce the ordinary crops. With an overall efficiency of 50% for pump and motor, each acre-foot of water will require about 2 kWh of electricity for each foot of lift. New motor designs promise to reduce the costs of irrigation for fields remote from the main electrical service.

Methods of Irrigation. These include overhead pipes, stationary spray plants, and portable sprinkler systems. In the overhead type the discharge pipes are supported on posts and are located about 50 ft apart in lengths up to 600 ft. The pipes are usually supported on rollers so that they can be oscillated by a type of water motor, and nozzles are spaced 2 ft or more apart. Sixty gal/min of water per acre at 30 lb pressure is satisfactory. Stationary spray plants can reduce spraying time in orchards by 50% or more compared with portable units. A central pumping station, mixing tanks, and symmetrically located discharge pipes complete the layout. The pumps are usually three- or four-cylinder, single-action, with capacities of 10 to 60 gal/min at pressures up to 600 lb or more, requiring motors of 5 to 30 hp. Outlets are located at regular intervals for attaching the spray hose. Spray nozzles discharge up to 8 gal/min depending on pressure and orifice size. Power required is usually under 10 kWh/(acre)(application). Portable systems utilize lightweight, quick-coupled pipes, with sprinklers attached. Laid on the ground, they require considerable labor to move, but the initial investment is less than with other types. Sprinklers operate at pressures of 20 to 50 lb/in² and cover circles 40 to 90 ft in diameter, delivering 3 to 30 gal/min. A motor as small as 2 hp will apply 1 in water to 3 acres of land per week, although larger outfits are commonly used.

Grain Conditioning. Field harvesting and on-the-farm storage losses of small grains and ear corn can be materially reduced where mechanical crop-drying or conditioning equipment is utilized. Early harvest reduces field losses due to shattering or lodging of grain and shelling, which may occur during mechanical harvesting. Crops can be harvested when weather conditions are most favorable as soon as possible after they mature, thus reducing the chance of storm damage while the crop dries in the field.

Heated-Air Crop Dryers. Equipment needed includes an oil burner, a power-driven fan, and a drying bin for the ear corn or small grain.

Most of the dryers are portable. Each unit consists of a power-driven fan, a heater, and safety controls. Such dryers have two characteristics that determine their performance in drying grain: (1) the rate at which heat is supplied (rate of fuel consumption per hour) and (2) the rate of air supply in cubic feet per minute. These dryers are normally equipped with oil burners that consume fuel at the rate of 3 to 14 gal/h and fans powered by 3- to 5-hp electric motors that deliver 9000 to 15,000 ft³/min of air. Usually 9000 ft³/min of 30°F air, with a relative humidity of 70%, can be heated to 70°F with an oil consumption of 3 gal/h used in a direct-heat dryer and 4.2 gal/h for the dryer if a heat exchanger is used. The U.S. Department of Agriculture reports that 1000 bu of ear corn was dried from 30% to 13% moisture in 167 h.

Shelled corn, wheat, and oats can also be dried with heated air. Depth of grain in drying bins is 4 to 5 ft. Airflow must be uniform through grain, and temperatures of heated air should not exceed 110°F for seed corn and 140°F for wet milling. Temperatures up to 200°F have been used without affecting feed value.

Unheated-Air Crop Dryers. Wheat, oats, and barley are harvested in the summer, when atmospheric conditions are relatively favorable for grain drying with unheated air. Wheat combined at a moisture content as high as 20% can be successfully dried with unheated air. Minimum airflow is 3 ft³/min · bu with grain up to depths of 4 ft. With 16% moisture content, airflow may be as low as 1 ft³/min · bu with wheat up to depths of 8 to 10 ft.

21.3.6 Materials Handling

Conveyers and Elevators. Livestock and crop production requires much time and labor for loading, transporting, and unloading materials. Portable chain and flight conveyers, commonly called elevators, are available in lengths of 8 to 50 ft or more and in widths of 6 in to more than 20 in. They

may be operated at angles up to 70° , depending on the material being handled, but care must be taken to prevent overturning or collapsing, particularly at the greater angles. The smaller sizes are generally used for moving loose, bulky materials such as small grains, chopped forage, and bedding and will require up to $\frac{3}{4}$ -hp motors. Larger sizes are mounted on wheels and are used for baled, bagged, and packaged products, as well as other materials. Power requirements range from $\frac{1}{4}$ up to 5 hp, depending on the speed, angle of elevation, and weight of the material being handled. Vertical elevators for baled hay are mounted directly to the outside of barn walls. A 42-ft model will require a 2-hp motor.

Auger conveyers requiring fractional-horsepower motors are used for the horizontal and vertical moving of grains. Automatic feeding arrangements may employ 10-in-diameter forage augers in multiples of 5- or 10-ft sections up to 100 ft in length. Three-horsepower motors are required for lengths up to 90 ft, and 5 hp is needed for longer units. *Pneumatic conveyance* of grains and feed is increasingly popular on farms where the distance between storage or processing areas and feeding areas is considerable. This method is safe, has few moving parts, and is dust-free. The pipe can be placed in almost any path, above- or belowground. An air velocity of 4000 ft/min is required for proper operation with a 5-in pipe conveying about 4500 lb of grain/h. This will require $2\frac{3}{4}$ hp for each 100 ft of length.

Silo Unloaders. Mechanically operated silo unloaders remove the silage from the silo and deposit it at the foot. The operating mechanism of the top-unloading type is essentially a radial beam with scrapers or augers which collect the silage and bring it to the center of the silo, where it is picked up by a motor-driven air or mechanical device and delivered to the silo chute. Silage then falls down the silo chute, where it is collected for feeding.

There is also a bottom type of silage unloader. The operating mechanism consists of an endless chain mounted on a movable beam. The chain is equipped with scrapers which move the silage out of the silo as the chain revolves.

Unloaders eliminate the need for climbing the silo daily, reduce spoilage by removing silage at a uniform depth, and save up to 200 h/year of time. Results of Ohio State University tests indicate that top removal of grass silage at a rate of 1 ton/h requires 4.3 kWh and that 1.6 tons/h of corn silage requires 2.5 kWh. Three- to ten-hp motors operate the unloaders, and approximately 300 kWh is used annually.

Barn Cleaners. Electrically operated mechanical devices remove manure from poultry, dairy, and livestock barns. In poultry houses the cleaners may be placed under a slatted floor or in a wire-covered pit under tiers of mechanical feeders and waterers. In dairy barns they are installed in the gutters behind the cows. The dragline type uses a motor-driven drum to pull a belt or chain conveyer, equipped with cross flights, to an inclined elevator at the end of the barn, depositing the manure in a field spreader or pit.

The endless-chain type is well adapted to the larger stable where two rows of cows are housed. A single chain with wood or steel paddles travels around the gutters and up a short elevator, discharging the manure outside the stable. In this type of installation connecting or cross gutters must be installed at each end of the two rows of existing gutters so that an endless chain can be installed. The oscillating type uses a reciprocating bar with hinged paddle or auger conveyer. Portable types generally use a scoop steered by the operator and drawn along the gutter by a cable attached to a motor-driven drum. Cleaners are operated by electric motors of 2- to 5-hp capacity. They can be set to operate automatically for a predetermined cleaning period or can be switched on as need arises. Electric-energy use ranges from $\frac{1}{2}$ to 1 kWh a month for each cow housed in the stable.

21.3.7 Maintenance

Emergency Power. With increased dependence on electric power for time-controlled mechanical feeding, pipeline milking systems, manure removal, etc., the added investment in emergency power units may be justified compared with the possible economic loss if regular power fails. Generators ranging from 3 to 15 kW and rated at 120/240 V are available in tractor power-takeoff (PTO) and

engine-driven types. The latter may be manually or automatically started. Automatic generators must be of higher capacity, because peak-connected loads will be carried if power fails. Nonautomatic types should have a “power off” alarm and must be PTO-equipped with an overload circuit breaker. The tractor PTO-driven generators are least expensive to purchase, as the tractor engine serves as the generator drive. Output is controlled by an engine tachometer and/or voltmeter in the generator unit. Manufacturers claim a voltage rating within 2% of the normal supply voltage. Required generator capacity is obtained by totaling the power needs of essential loads, plus allowances for future loads and high starting currents of the motors. Double-throw switches must be used at the point of connection into the wiring, to prevent generator damage and power feedback into the supply line.

Arc Welders. A highly mechanized agriculture requires that many machinery and structural repairs be made by the farmers themselves. A survey by the Kansas Farm Electrification Council indicates that the number of dollars invested in electric welders was greater than for any other item of electric farm equipment. The electric arc welder is inexpensive, efficient, and an almost indispensable tool on modern farms. The 180-A transformer-type ac welder is satisfactory for most farm shops. This machine can cut, hard-surface, and weld metals up to $\frac{1}{2}$ in thick. It requires a line voltage of 220 to 240 V single-phase, 60 Hz. Current outputs from 30 to 180 A are possible. Duty cycle at maximum output is 20% with an open-circuit voltage of 25 V. A carbon-arc-torch attachment is used for brazing, soldering, and heating purposes. Larger generator-type units, either engine or tractor PTO-driven (hence portable), may be used as emergency power generators, supplying 5000 W of 230- or 115-V single-phase 60-Hz power.

Phase Converters. Most farms have 100- or 200-A single-phase service, which limits them to the use of $7\frac{1}{2}$ - or 10-hp motors. Two types of phase converters are available which will convert single-phase to 3-phase current. By connecting the converters between the electric meter and the motor, they will permit the use of 3-phase motors up to 20 hp or more. In addition, the *National Electric Code* states that service entrances need be heavy enough to handle only the largest-power-demand equipment, plus a portion of all other equipment, rather than the total connected load as before. This is advantageous where irrigation pumps, grain dryers, large feed mills, etc., are in use.

Other Shop Equipment. This includes electrically powered air compressors, drill presses, grinders, hoists, lathes, saws, and paint sprayers. These generally require $\frac{1}{4}$ - to $\frac{1}{2}$ -hp motors. Battery chargers drawing approximately 2 kWh/charge are popular.

21.4 THE FOOD INDUSTRY

The food industry is diverse, essentially composed of eight sectors: dairy, processed fruits and vegetables, breakfast cereals, wet corn milling, bakery products, sugar and confectionery, fats and oils, and alcoholic beverages. The industry relies on a variety of energy sources.

Food manufacturing processes are as diverse as the industry itself. They can be as simple as boiling a potato or as complex, intricate, and technical as converting corn into starches, sweeteners, and corn oil. In between these two extremes are numerous processes with varying degrees of technological complexity, requiring a mixture of physical, thermal, and biochemical transformations.

One of the simpler food production processes is liquid heating, essentially applying heat through water or some other medium. For example, water temperatures of 125°F and above are required for the scalding of poultry, while pressure cooking involves the application of steam in rotation cookers. In the beverage industry, boiling converts insoluble starch into liquefied starch to obtain brewer's malt. Baking involves the application of heat to cook or brown foods. Baking and roasting apply heat directly to the foods. Frying uses a transfer medium—typically oil. Baking is used extensively in the bread-and-cookie industry. The more complex processes also involve the application of thermal energy to effect chemical or biochemical changes in the composition of foods. Temperatures above 140°F are required to pasteurize milk.

Food preservation techniques include thermal processing, moisture removal, chemical processing, and irradiation. Cooking, boiling, baking, and other procedures use heat to inactivate microorganisms, enzymes, or harmful chemicals in food. Removal of some of the moisture in foods often extends the length of time during which the product can be stored without spoilage, such as in dehydration. Current dehydration techniques include warm, hot air, or steam; freeze drying for coffee and herbs, and the concentration of milk and fruit juices; and microwave and vacuum technologies. The chemical additives most commonly used with food are salt and smoke (used in curing and smoking operations). The last type of food preservation technique is a recent introduction: ionizing radiation—or irradiation—which uses gamma rays, electron beams, and x-rays to sterilize a variety of products. This sterilization is brought about by a chemically induced destruction of insects and microorganisms which would otherwise accelerate the spoilage process. The industry is critically dependent on energy for food preservation.

The most electricity-intensive food-processing sectors are wet corn milling, meat-packing plants, fluid-milk producers, soybean-oil mills, malt beverages, frozen fruits and vegetables, poultry dressing plants, bakeries, flour-milling plants, and soft-drink plants. Most of these consume large amounts of electricity because of their size.

21.5 THE TEXTILE INDUSTRY

The textile industry consumes raw materials from the agricultural and chemical industries and supplies raw materials to producers in the home furnishings (accounting for 45% of industry output), apparel (30%), and industrial fabrics industries (25%). Overall energy consumption in the textile industry has increased in response to industry growth and productivity improvements. Electric machine drives account for 57% of electricity use, lighting and other facility services consume 23%, and HVAC systems account for about 14%.

In response to increased foreign competition, the textile industry has had to invest in productivity and efficiency improvements. Productivity improvements are reflected in increase in the amount of energy consumed per employee. This increase is largely attributable to increased process automation. Improvements in energy efficiency are evident in the decreased amount of energy consumed per value of shipment. The textile industry uses large amounts of energy in process heating. Although large electric and thermal loads provide attractive opportunities for cogeneration, cost pressures have constrained cogeneration investments.

In response to highly competitive market conditions, textile manufacturers have adopted “quick response” (QR) systems that improve communication between suppliers, manufacturers, and end users. Although QR systems are fundamentally information technology systems that are not themselves energy intensive, they provide opportunities to increase the level of automation in a facility.

The most electricity-intensive textile plants are greige mills, which produce unfinished woven and knitted goods. Electricity supplies about 80% of the total energy requirement in a greige mill. The application of mechanical moisture-removal equipment such as vacuum extractors and roller squeezers is expected to impact electrical plant design and consumption, primarily as a result of the potential energy savings and process simplification in textile drying and finishing.

21.6 THE PETROLEUM INDUSTRY

The petroleum refining industry encompasses a broad range of operations that provide raw materials to almost every manufacturing industry. Petroleum refiners produce fuels and solvents—lubricants that are essential to the operation of most industrial facilities. Additionally, petroleum refiners produce feedstocks for the plastics and petrochemical industries.

Electricity accounts for about 3.5% of the industry’s total energy use. About 80% of the total electricity consumption is used to operate pumps, compressors, fans, and other machine-driven applications.

21.6.1 Oil Refineries

Introduction. Oil refineries are seeking to maintain or increase their profit levels by upgrading existing processes and replacing aging equipment with more efficient and lower-operating-cost options. In the petroleum refining process, the primary raw material, crude oil, is heated, separated, and converted into up to 10 major product categories: motor gasoline, fuel gas, liquefied petroleum gases (LPGs), jet fuel, diesel fuel, lubricants, kerosene, fuel oils, asphalts, and coke.

In the United States, motor gasoline and jet fuel provide the highest revenue and are produced in the highest quantities. Diesel and home heating oils and residual fuels used by power plants, ships, and industrial boilers are also important products that contribute to the industry's bottom line. Each refinery has a varied product slate, the mix of products produced in response to market demands.

Generally speaking, a refinery can be classified as one of three types: gasoline (cracking), fuel oil (hydroskimming or topping), and coking. A gasoline refinery produces a greater percentage of gasoline and less heating and other heavy oils. The refinery increases its gasoline yield by upgrading the heavy oils. A fuel oil refinery primarily produces ship, industrial, and home heating oils, some gasoline, and kerosene. A maximum amount of gasoline and a much reduced percentage of heavy oils are produced in a coking refinery.

General. Oil refineries vary greatly in the variety and quantity of products and crude-oil throughput. A basic refinery producing gasoline and other fuel products would include operations such as those described below. These are merely typical of the many processes in current use.

Crude-Oil Desalting. Water is added to the crude oil to dissolve the unwanted salt. The mixture is passed through a vessel containing electrodes between which a potential of several kilovolts is maintained. The potential gradient causes the salt and water to coalesce and settle to the bottom of the vessel, where the mixture is drawn off. The desalted crude oil is discharged near the top of the vessel.

Crude-Oil Distillation. The crude oil, which is a mixture of a large variety of hydrocarbons having different boiling points, is heated in a furnace to about 750°F and then enters a fractionating tower. The components are separated according to boiling range, since the lighter ones rise in the tower as gases and the heavier ones fall in the tower as liquids. Trays with specially designed openings in them are installed at intervals in the tower to ensure intimate mixing of the rising gases and the falling liquids and to provide places where liquids having certain boiling ranges may be drawn off the tower. The operation is first performed in a distillation tower in which the pressure is maintained somewhat above atmospheric pressure and again in another tower which is kept under vacuum in order to reduce the boiling temperatures of the hydrocarbons and thereby prevent thermal cracking, which is decomposition due to excessive heat. The combined unit is called an atmospheric and vacuum, or A&V, unit. It is also sometimes called a "two-stage pipe still." The main fractions produced are condensable gas, gasoline components, diesel fuel, heating oils, gas oils, and residuals. All of these are processed further.

Fluid Catalytic Cracking. To increase gasoline yield from a crude oil, heavy gas oil from the distillation unit is processed in a cracking unit. The heavy molecules are brought in contact with a catalyst under proper conditions of temperature and pressure and are converted into lighter molecules. Thus lighter products are formed which are suitable for use as gasoline and distillate fuel components. The use of a catalyst promotes the cracking reaction at a lower temperature and pressure and produces larger quantities of products having more valuable qualities than is possible with straight thermal cracking.

The clay catalyst is in powder form, and it is handled as a fluid. The cracking reaction causes the formation of carbon deposits on the catalyst particles. These are removed by controlled burning in a regenerator vessel. The catalyst is continually being circulated through the reactor and the regenerator by means of gas flow and airflow, respectively.

Combustion Air Blower. Combustion air for the regenerator is provided by a large centrifugal air blower driven by an induction motor and gear increaser or by a steam or gas turbine.

Gas Compressor. Some of the products of the catalytic cracker are drawn off as gas. This gas is compressed, condensed, and fractionated to provide other fuel products and feedstocks for petrochemical processes. A centrifugal compressor is used, and it is driven by an induction motor through a gear increaser or by a directly coupled steam turbine or gas turbine.

Catalytic Re-forming. In this process hydrocarbon molecules are rearranged and recombined to form molecules of higher octane rating which can be used as gasoline components. Hydrogen is produced in this process. Large reciprocating and centrifugal compressors are used to move the large volumes of gas involved in the process. Hydrogen is a by-product of this process.

Hydrofining. This process uses hydrogen in the treatment of other products, such as jet fuels, distillates, and lubricating oils, to improve quality and to remove sulfur.

Cooling-Water Pumps. Large volumes of water are used for cooling-process streams and for condensers. Water may be conserved by the use of induced-draft cooling towers.

Cooling-water circulating pumps are driven by vertical motors. Standby pumps are driven by steam turbines.

Power Supply. Refining operations are continuous processes, and uninterrupted runs of 1 or more years are expected between planned shutdowns for maintenance or turnarounds. Therefore, it is essential that the power supply be extremely reliable.

Often duplicate full-capacity feeders are installed to the refinery, and sometimes these are run from different substations, for increased security. Many refineries practice cogeneration to take advantage of their high steam loads.

Distribution Systems. Because refinery loads are often concentrated to a large extent in fairly well-defined process areas, it is common to install unit substations in the major process areas. These substations contain power transformers to provide 4160- or 2400-V power, 480-V power and lighting transformers, or provision for feeding lighting transformers. They also contain all associated switchgear, motor-control, and emergency generators.

A typical refinery *process-unit distribution* system is shown in Fig. 21-2.

Area Classification. Flammable gases and vapors are processed in oil refineries. Therefore, it is necessary to classify the various locations according to the material that is present and also according to the degree of hazard expected.

Reference should be made to the applicable electrical code for requirements governing installations in classified areas.

The actual classification of areas is usually made by the electrical design engineer in consultation with persons who are familiar with the operation of the process.

The most common classification for refinery process units is Class I, Group D; the class consists of hazardous gases and vapors, and the group comprises gasoline and many of the petroleum products.

Current practice is to classify outdoor, freely ventilated process areas as Division 2. Indoor process areas that are not freely ventilated and places below grade level are classified as Division 1. Areas in which a permanent ignition source is located, such as around a furnace, are not classified. Pressure-ventilated unit substations and control buildings are not classified. However, some companies follow the practice of classifying control rooms as Division 2.

21.6.2 Electric Motors

Type of Motor. Two-pole induction motors having NEMA Design B characteristics are used to drive the majority of refinery-process pumps. Motors operating at slower speeds are used for some applications, such as for driving reciprocating compressors or for driving centrifugal compressors through gear-speed increasers.

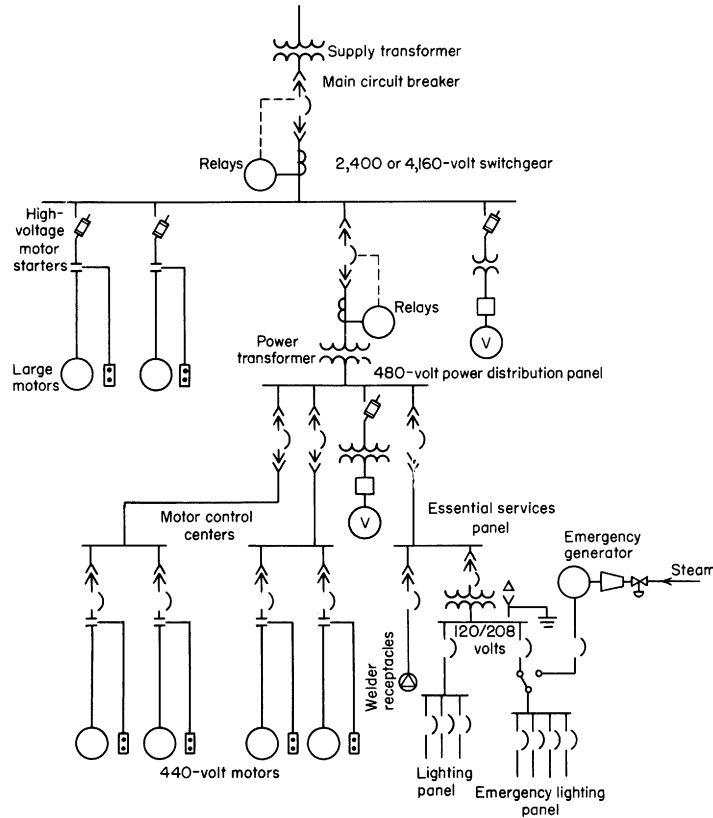


FIGURE 21-2 Typical refinery process-unit distribution system.

21.6.3 Emergency Power Supply

Emergency Generator. Generators provide emergency power for critical motor loads, emergency lighting, and instruments. Generators are driven by steam turbines or diesel engines, which start automatically when the normal refinery power supply fails. Capacities range from 15 to 300 kW. Output voltage is 120/208 V 3-phase or 480 V 3-phase. Load is automatically transferred to the generator after it has reached normal operating speed.

Batteries. Batteries are used when a continuous supply of power must be available for process instruments, emergency controls, and shutdown devices. They are also used for remote-control systems. Voltages of 24, 48, and 120 V are used. Inverters provide power for critical ac instruments and are sometimes used for computer power supply. Battery chargers are transferred to the emergency generator on loss of normal power.

Batteries should have enough capacity to carry full load for half an hour with the charger off. Charger capacity must be sufficient to carry the full dc load and to recharge the battery in 8 h.

21.6.4 Oil-Well Pumping

Methods of Forced Production. When there is insufficient natural pressure to force the crude oil to the surface, some method of forced production is used. The most common methods are described as follows.

High-Pressure Gas Lift. Gas is forced to the bottom of the well or to an intermediate point in the well. The gas mixes with the oil in the well and induces flow by decreasing the density of the fluid.

Water Flooding. Treated water is forced into the formation through nearby wells in order to increase the pressure in the formation and induce flow.

Bottom-Hole Hydraulic Pump. High-pressure crude oil is carried down the well in tubing, and it is used to drive a reciprocating pump located at the bottom of the well.

Bottom-Hole Centrifugal Pump. A special motor-driven multistage centrifugal pump is lowered to the bottom of the well. This method is used where large volumes of fluid must be pumped.

Sucker-Rod Pump. A reciprocating single-acting pump is installed at the bottom of the well on the end of a tube inside the well casing. In sucker-rod pump drives, the plunger is operated by a sucker rod from the surface. Various methods are available to drive the sucker-rod string, but generally a walking beam is used to provide the desired vertical motion.

Central Power Units. Central power units driven by electric motors are sometimes used to serve as many as 15 or 20 wells. Operating rods lead out to each pump to provide reciprocating motion to the walking beams.

Individual Engine or Motor Drives. These are more commonly used than multiple drives because they can be started and stopped individually and the pumps can be operated at different speeds. Electric motor drives are preferred because they can be started and stopped by a timer, they provide consistent, trouble-free performance regardless of weather conditions, and maintenance and investment costs are low. Also, it is easy to measure power demand and energy consumption of an electric motor. The well may be counterbalanced readily by an ammeter.

Motor Types. Torque requirements vary widely during the pumping cycle, and peaks occur when the sucker-rod string and fluid load are lifted and when the counterweight is lifted. NEMA Design D motors, although relatively expensive, are well suited to this service, since they minimize current peaks and provide adequate torque under all service conditions, including automatic operation by time control. NEMA Design C motors may be used where operating conditions are less severe. NEMA Design B motors must be used with care in this service to avoid high cyclic current peaks, which may be objectionable on a small system, particularly if several wells should "get in step." The use of Design B motors can also lead to oversizing of motors in an attempt to obtain sufficient starting torque. This results in the operation of the motor at a relatively low load factor, with consequent low power factor.

Double- or Triple-Rated Motors. These are special motors developed for oil-well pumping. They are totally enclosed, fan-cooled NEMA Design D motors that can be reconnected for 2- or 3-hp ratings at a common speed of 1200 r/min. Typical horsepower ratings are 20/15/10 and 50/40/30. They provide flexibility in the field since they permit the selection of the horsepower rating at which the motor may be operated most efficiently. They also permit changing the pumping speed by changing the motor pulley and reconnecting the motor.

Single-Phase Operation. If single-phase power only is available, it is advisable to consider the use of single-phase/3-phase converters and 3-phase motors. This avoids the use of large single-phase capacitor start motors, which are relatively expensive and contain a starting switch which could be a source of trouble due to failure or to the presence of flammable gas in the vicinity of the well.

Oil-Well Control. A packaged control unit is available to control individual oil-well pumps. It contains, in a weatherproof enclosure, a combination magnetic starter, a time switch that can start and stop the motor according to a predetermined program, a timing relay that delays the start of the motor following a power failure, and lightning arresters. Push-button control is also provided.

Power-Factor Correction. The induction motors used for oil-well pumping have high starting torques with relatively low power factors. Also, the average load on these motors is fairly low.

Therefore, it is advisable to consider the installation of capacitors to avoid paying the penalty imposed by most power companies for low power factor. They will be installed at the individual motors and switched with them, if voltage drop in the distribution system is to be corrected as well as power factor. Otherwise they may be installed in larger banks at the distribution center, if it is more economical to do so.

21.6.5 Gas-Processing Plants

Natural Gas. Natural gas varies widely in composition and contains undesirable materials such as water and sulfur compounds, which must be removed before the gas enters the transmission pipeline. Various chemical processes are used, and plant capacity ranges from 5 to 1000 million ft³ of gas processed/day. By-products such as propane, butane, pentanes, and elemental sulfur are produced and marketed.

Power Supply. Purchased power is used where available. Local generation is by reciprocating gas engines or gas turbines.

Electrical installation practice in gas plants is similar to that followed in oil refineries, as described below.

21.6.6 Oil Pipelines

Gathering Systems. These collect crude oil from the individual wells, or from tanks located near them, and carry it to tankage, where shipments may be accumulated.

Trunk Lines. These feed crude oil from gathering systems to the main crude pipeline pumping station.

Crude Lines. Crude lines are generally operated as common carriers. Since they handle crude oil for several companies and because crude-oil shipments vary greatly in quality and composition, storage tanks are necessary at stations along the pipeline so that batch shipments may be handled.

Product Lines. These convey products from a refinery to the market area. Some products lines are operated as common carriers, while others are privately owned and operated.

Operation of Pipelines. Batches of crude oil or products are dispatched through a pipeline and are withdrawn to tankage at the end of the line or at intermediate points. If a batch is being drawn off at an intermediate point, the downstream stations will operate at reduced flow.

Little mixing occurs at the interface between different batches. By careful scheduling and a knowledge of the pipeline it is possible to predict fairly accurately when an interface will arrive at a station. Interface detectors are installed also.

Pumping Stations. A schematic diagram of a typical pumping station is shown in Fig. 21-3.

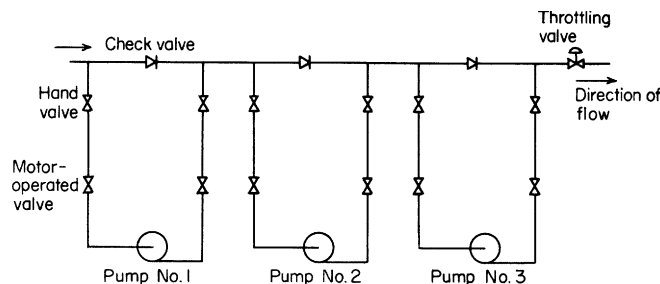


FIGURE 21-3 Pipeline pumping station.

Arrangement of Pumping Stations. These are located at the head of the pipeline and at intervals along the line. Intermediate or booster stations must be capable of operating under varying conditions due to differences in liquid gravity, withdrawals at intermediate points, and the shutting down of other booster stations. Pumping stations often contain two or three pumps connected in series, with bypass arrangements using check valves across each pump. The pumps may all be of the same capacity, or one of them may be half size. By operating the pumps singly or together, a range of pumping capacities can be achieved.

Throttling of pump discharge may also be used to provide finer control and to permit operation when pump suction pressure may be inadequate for full flow operation.

Control of Pumping Station. Pumping stations are often unattended and may be remotely controlled by radio or telephone circuits.

Electrical System. Figure 21-4 is a typical electrical single-line diagram for a pumping station.

Motor Type for Main Pumps. The main pumps are driven by 3600-r/min induction motors having NEMA Design B characteristics. Full-voltage starting is used.

Motor Enclosure. Motor enclosures for outdoor use are NEMA weather-protected Type II, totally enclosed, fan-cooled, or dripproof with weather protection. Motors of the latter type are widely used. Not only are they less expensive than the other types, but they also have a service factor of 1.15. The above enclosure types are all suitable for the Class I, Group D, Division 2 classifications usually encountered.

If the pumps are located indoors, a Division 1 classification is likely to apply. Motors must be Class I, Group D, explosionproof, or they may be separately ventilated with clean outside air brought to the motor by fans. Auxiliary devices such as alarm contacts on the motor must be suitable for the area classification. The installed costs, overall efficiencies, and service factors associated with the enclosures that are available will influence the selection.

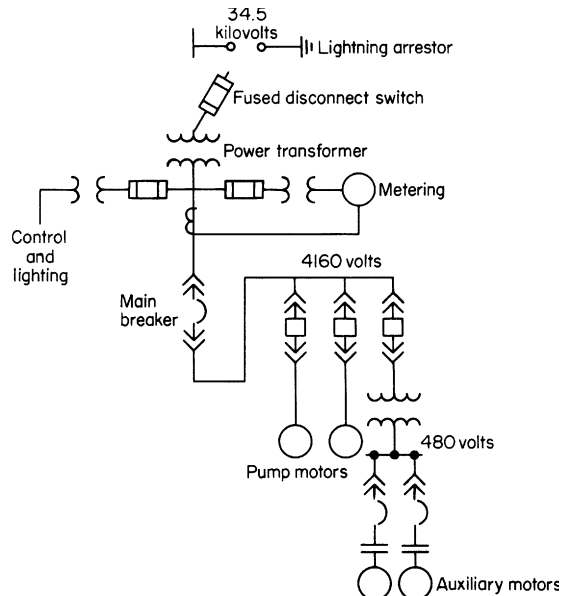


FIGURE 21-4 Single-line diagram of a pipeline pumping station.

Adjustable-Speed Drives. Of the total electricity consumed by petroleum refiners, 80% is for machine-drive applications. Most of this energy is used to drive turbomachinery such as pumps, compressors, and fans. These applications are well suited for adjustable-speed drives. Since the power consumed by turbomachinery is highly dependent on operating speed, the use of adjustable-speed drives to control the output of these machines can provide significant improvements in operating costs and system performance. The most common type of adjustable-speed drive is the *variable-frequency drive* (VFD), which uses rectifiers and inverters to control the frequency of the power supplied to a motor. VFD technology is widely used in industry, providing energy savings up to 70% below conventional flow control options.

Pumping systems are particularly attractive applications for VFDs. Because of the reduced amount of wear on system valves and piping supports that results from minimizing unnecessary pump output, VFDs can improve system reliability and lower maintenance costs.

21.7 THE STEEL INDUSTRY

Industry Description. The domestic steel industry includes blast-furnace integrated steelmakers, nonintegrated minimills, and independent producers of wire, bar, and pipe made from raw steel. Blast-furnace operations use either an open hearth or a basic oxygen furnace, with electric arc furnace used in the minimill. Raw steel is melted increasingly by electric furnaces, and the basic oxygen furnace is still used in a number of mills.

Energy Use. The steel industry is highly energy-intensive. Its aggregated average energy consumption of approximately 19 million Btu per ton of steel shipped represents about 3% of the energy consumed in the United States and 10% of that used by the industrial sector. Approximately 60% of the energy consumed by the steel industry is derived directly from coal, and much of the electricity the industry uses is generated at coal-fired power plants.

Natural gas accounts for nearly 30% of the industry's energy consumption. Energy purchases represent about 15% to 20% of the total manufacturing cost of steel. In response to these significant costs, the industry has sought to improve production efficiency, principally through process modifications, new technology, and the retirement of old or inefficient plants. Since 1975, the steel industry has reduced energy consumption per ton of steel shipped by about 45%. The steel industry blast furnace process lends itself naturally to cogeneration by virtue of the large amount of by-product gases generated. The industry today recycles a high percentage of scrap steel, and uses fuels that are by-products from the cokemaking and ironmaking processes to cogenerate electricity and steam. Additionally, the industry has replaced a number of their open-hearth furnaces with basic oxygen furnaces and has implemented continuous casting on a wide scale.

Electricity as a Cost of Making Steel. The U.S. steel industry is a major consumer of electricity. Energy costs account for 15% to 20% of the total manufacturing cost of producing steel. Electricity on average represents only about 7% of the total energy consumed by the industry, but at some steel plants over half of the purchased energy is in the form of electricity. Costs of electrical energy are disproportionately higher than those for other forms of energy.

Power-Distribution System. Integrated steel mills having blast furnaces and coke plants make use of the combustible gases from these processes by burning them to produce power and process steam. Many older steel plants produce and use power at 25 Hz, utilizing primary distribution voltages of 6.9 to 13.8 kV and secondary systems of 4160 or 2400 V and 480 V. Modern steel plants and modern parts of older plants utilize 60-Hz power exclusively, with primary distribution at 69 or 138 kV and secondary voltages of 13.8 kV, 4160 or 2400 V, and 480 V. Power can be supplied by public utilities, by in-plant generation, or by a combination of the two. Some plants having both 25- and 60-Hz systems have conversion equipment, typically large Scherbius sets or rectifier-inverter systems, for

transfer of power from one frequency to the other. Where power is supplied from both a public utility and in-plant generation, there is usually some provision for controlling the maximum demand and improving the power factor of the portion of the load supplied by the utility to avoid high penalty charges.

The presence of numerous cranes and other equipment requiring dc motors with some control over speed has led to the extensive use of 250-V constant-potential dc shop circuits in most steel mills. In older plants the direct current is supplied by rotary converters, motor-generator sets, or mercury-arc rectifiers. In modern plants it is supplied by silicon diode or thyristor rectifiers. The trend is toward the elimination of dc shop circuits by the use of ac cranes and package thyristor power supplies for drives requiring variable speed.

Primary Production. The basic steelmaking areas of an integrated steel plant consist of *coke-oven batteries* for conversion of coal to coke, *blast furnaces* for conversion of iron ore to molten iron, and *steel-producing units* for refining molten iron and other alloy ingredients to steel. Once this basic steel has been produced in ingot (block) form or “continuous cast” into semifinished bars, it is ready for subsequent rolling into a usable size and shape.

Power consumption per ton of steel produced is low in the basic steelmaking areas because the products are handled in molten or bulk form, compared with the rolling mills, where reheated or cold steel is literally squeezed and stretched to the desired size and shape. Much of the electric power consumption in these primary producing areas is associated with auxiliary drives involved in material handling, water, air, and by-product utilization, and mobile equipment.

The processes of iron reduction and steel refining, with their many, sometimes elusive, variables, do lend themselves to automatic and computer control. Open-loop computer systems have been applied to *blast-furnace* and *basic-oxygen-furnace* (BOF) operations. Raw-material handling and charging functions in *blast-furnace stock houses* and BOF have been automated extensively.

In a minimill, which includes specialty shops, the basic raw material is steel scrap which is melted and refined to produce raw steel and steel products. The steel is melted by an electric arc in which the current passes from one electrode through an arc to the scrap charge, and then from the charge to another electrode. The molten steel is then refined by rapid oxidation and the reaction of impurities with added slag materials.

Rolling Mills. Rolling mills are classified either according to their construction or according to the material processed. Classified according to construction, mills are generally two-high or four-high, with a few existing three-high mills. Four-high mills consist of the usual two work rolls in contact with the product, with two additional “backup” rolls which are much larger and allow high rolling pressure without excessive deflection of the work rolls. A “universal” mill has vertical or edging rolls in tandem with the horizontal rolls. This permits a reduction of width or control of the edges of the product in the same stand where a reduction in thickness is taking place.

The principal types of mills, classified as to product rolled, are as follows.

Blooming Mills. These mills roll ingots into blooms, or slabs. All material rolled in steel mills, except that which is direct continuous cast into slabs, blooms, or bars, first passes through this type of mill, or its equivalent, to be reduced to proper dimensions for handling in the finishing mills. These are generally single-stand, two-high reversing. Slabbing mills are a modification of the blooming mill. They are usually universal mills, which permits convenient rolling of wide slabs by eliminating frequent turning of the ingot. Blooming and slabbing mills may have such automatic features as preset of roll openings and speed synchronization between main and edger rolls. The preset information is sometimes stored on business-machine cards and read into the mill control system by a card reader, or it can be stored in the computer memory in computer-controlled installations. Blooming and slabbing mills are powered by large low-speed dc motors operating from a variable-voltage system. A typical slabbing mill has a total of four 3000-hp motors driving the horizontal rolls and two 2000-hp motors driving the edger rolls at rated motor speeds of 40 to 80 r/min. The dc power for blooming mills has been traditionally supplied by generators using the Ilgner system, but the present trend is toward the use of thyristor power supplies connected in rectifier-inverter configurations.

Hot-Strip Mills. These mills roll sheets, strip, and plate from heated slabs. These mills can be placed in two categories: continuous and semicontinuous. (These terms designate the type of rougher which precedes the finishing train.) The *continuous mill* has two to six mills in line which reduce the slab to a predetermined thickness for subsequent rolling through the finishing train.

The *semicontinuous mill* has a reversing rougher on which reduction is made by running the piece back and forth through the mill, which reduces the slab to a predetermined thickness for subsequent rolling through the finishing train.

The finishing train consists of five to seven stands, closely coupled and synchronized in speed, in which the piece is reduced to the desired gage. As a general rule, the piece is in all finishing stands simultaneously.

Roughing stands of a continuous mill are usually driven by ac motors, since speed synchronization with an adjacent stand is not required. Many existing roughing mills utilize wound-rotor induction motors with flywheels and water-slip regulators, but today synchronous motors predominate. The roughers on semicontinuous mills are driven by dc motors.

Direct-current motors operating from a variable-voltage system have been traditionally used for finishing stands, but ac motors with variable-speed drives are now being used in some applications. Tension between stands must be accurately controlled at a relatively low value, since the hot steel is in plastic form and excessive tension results in “necking,” or breaking. Constant-tension “loopers” are used between stands for interstand tension regulation. The looper is pushed up by air, hydraulic pressure, or a torque motor, and the upward movement is restricted by the strip. The looper position is then fed back to the electrical control system, and the speed of individual finishing-stand motors is regulated to maintain the proper looper position.

Various measuring devices must always be in operation, measuring gage, screw position (roll opening), looper position, roll force, and width of strip. With the feedback from these devices, the positioning of the screw-downs, which control gage, and the edgers, which control width, can be regulated during the rolling of the strip. The newer mills make use of digital positioning to set up the mills prior to the entrance of the bar into the mill.

The thread-speed reference is set into the speed controller, and this speed is maintained by utilizing the pilot-generator feedback. When the strip enters the mill, the load increases sharply, bringing the current feedback to the armature controller into effect. By controlling the armature and field, rapid speed changes while complete control is maintained are possible, both with and without load. The acceleration control, when called on, feeds into all the finishing-mill motors for uniform acceleration.

Newer mills now have small digital computers controlling each stand.

As the strip cools during rolling, it becomes harder and the output gage changes. Part of this change in gage can be controlled by accelerating the mill, but much of it must be controlled by changing the position of the screw-downs. The newer hot-strip mills use automatic gage control systems (AGC) to regulate screw-down position while the strip is in the finishing mill. There are two types of AGC in use, a constant-gage system and an absolute system. Both systems work basically the same, by taking a reference either from the head end of the strip in the constant-gage system or from preset switches in the absolute system and maintaining it throughout the length of the strip. This reference is compared with the actual gage of the strip, measured as a function of roll force and screw-down position, or by an x-ray gage, and the screw-downs are moved to bring both these signals to the same value. This is a continuous operation during the period of time the strip is in the finishing mills.

Most modern hot-strip mills are built with computer control. Rolling in a completely automatic or computer-controlled state, the computer provides the position and speed references instead of operators. With a computer-controlled mill, these references can be constantly changed as the computer receives new information from the strip.

The handling of steel between roughing stands and between the finishing stands and the downcoilers is accomplished by roll “tables,” which are a series of motor-driven rolls on which the steel lies. In some installations, one large table motor drives a number of table rolls through mechanical gearing and shafting (“line-shaft drive”); in others, each roll is driven by one small motor. Permanent-magnet field dc motors have been particularly successful for this arrangement. Table rolls have been driven by dc motors operating from a variable-voltage system, but newer applications use

variable-frequency induction-motor system. As adjustable-frequency power supplies have become more reliable, this system is becoming standard.

Tandem Cold-Strip Mills. These are used to cold-reduce previously rolled hot-strip mill products down to thicknesses as low as 0.002 in. Special "foil" mills have been built which can roll even lighter gages. A cold-strip mill is similar to the finishing stands of a hot-strip mill, except that tension between stands plays a much more important role in reducing the thickness of the steel. Modern cold-strip mills are built for finishing speeds in excess of 5000 ft/min.

Cold-strip mills are generally three- to six-stand mills, four-high, with a coil box or payoff reel on the entry end and a tension reel at the delivery end. Newer cold-strip mills are universally driven by variable speed ac motors. Usually the individual stands are voltage-regulated, and the operator establishes the motor field and, thereby, the stand speed according to the gage reduction and the strip tension desired. Load-cell tensiometers are used to indicate to the operator the interstand tensions.

Some of the most modern mills have each stand speed-regulated, and all major drives incorporate full field acceleration to base motor speed for maximum torque. Above base motor speed, automatic field weakening with constant rated armature voltage is used to attain top motor speed. Payoff-reel tensions, interstand tensions, and winding-reel tensions are accurately controlled by using load-cell tensiometers to measure tension and provide feedback to tension regulators which operate on the appropriate drives (see Fig. 21-5).

Finished steel gage is controlled by utilizing x-ray gages to provide information to AGC regulators. Gage control may be accomplished by operating on interstand tensions only or by a combination of interstand tensions and work-roll openings. Work-roll openings ("screw-down positions") are controlled by digital position regulators which hold the screw-down position constant to within 0.0001 in. To help further in producing constant finished gage, the rolling forces on each stand are held constant by using speed-programmed digital regulators to hold constant rolling force at all speeds. Rolling force is measured and indicated by load cells placed under each stand housing.

Other Types of Rolling Mill. *Billet mills*, used to roll blooms into billets, are frequently of a continuous type with rolling stands in tandem with several sets of passes in the rolls so that different-sized billets can be produced from a given bloom without changing rolls. This type of mill is used for producing only a limited range of sizes, which are further reduced in finishing mills.

Plate mills produce plates from slabs previously rolled by a blooming or slabbing mill. These mills are generally single-stand mills, either two- or four-high reversing or three-high running

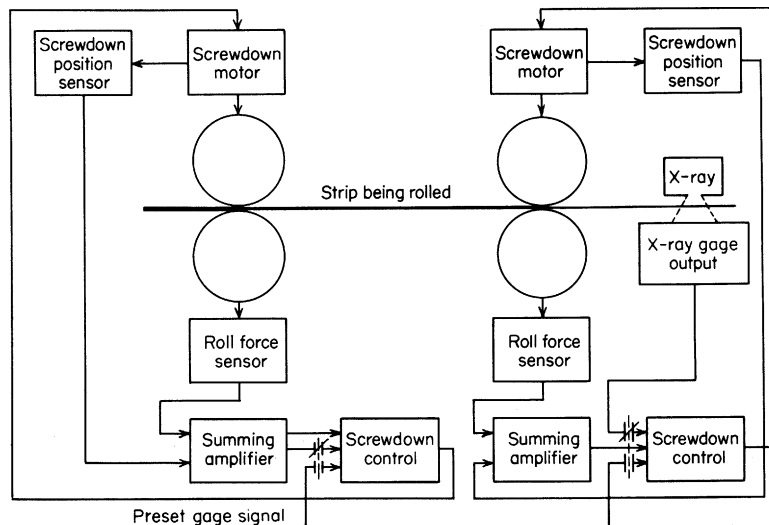


FIGURE 21-5 Cold-strip mill.

continuously in one direction, although some mills are provided with several stands in tandem, one serving as a rougher or breakdown stand. They are sometimes universal mills, provided with vertical rolls for finishing the edges of the plates.

Structural mills are used for rolling beams, heavy angles, channels, etc., from blooms or billets. Such mills rolling the smaller structural sections and miscellaneous shapes are sometimes called “bar mills.” They are frequently three-high, with more than one stand in line, and frequently have a separate rougher or breakdown stand. Some also have two-high reversing finishing mills with edger and vertical, as well as horizontal, rolls, to produce wide-flange (H) beams.

Rail mills are special mills for rolling this product only from blooms or billets, although rails are sometimes rolled on structural mills.

Merchant mills are used for rolling small angles, channels, rounds, squares, etc., from billets. This classification is generally applied to mills rolling the smaller sections used for miscellaneous purposes. Most are two-high, in tandem; however, some are arranged for cross-country rolling.

Rod mills are a specialized type of merchant mill for rolling small rounds, usually from No. 5 BWG and upward, which are later drawn into wire. Modern rod mills are arranged to roll a multiplicity of strands simultaneously.

Temper mills are used to produce steel strip of the desired temper, flatness, surface, and luster by using rolling pressure and tension. Reduction in thickness is incidental in the process and is normally very slight. Temper mills generally have one or two 4-high stands and are similar to cold-strip mills, except that they are of lighter construction, have less powerful motors, and have simpler electrical control systems. Temper mills have been built and operated at speeds in excess of 7000 ft/min.

Tube mills are used to produce tubes, for example, pipe and conduit, by either the seamless or the butt- or lap-weld process. Seamless mills pierce a solid billet and then form the pierced billet into tubes of the desired size and thickness. Butt- or lap-weld mills form and weld previously prepared pipe skelp into tubes.

21.8 THE CHEMICAL INDUSTRY

The chemical industry encompasses a broad range of manufacturers that provide essential raw materials for many other manufacturing processes. The largest energy users within the chemical industry are chloralkali facilities, industrial gases, inorganic chemicals, plastics and resins, synthetic rubber, organic fibers, cyclic crudes, nitrogenous fertilizers, and industrial organic chemicals.

21.8.1 Industrial Gases

The industrial gas facilities separate nitrogen, oxygen, argon, and carbon dioxide from air. These gases are then shipped in either liquefied or gaseous form. Some air separation plants build gas pipelines directly into large-volume contract customers.

Industrial gas production is electricity-intensive, accounting for 77% of the total industrial gas energy consumption. The process of separating air is primarily through a cryogenic technique. Air is compressed and cooled to temperatures below -200°F , then sent through turbines where additional energy is removed. After the air is liquefied, it is fractionated so that the component gases can be isolated. The gas products are then purified and reliquefied as required for shipment. The cryogenic technique is largely a mechanical vapor-compression process; consequently, motor drives account for about 87% of all electricity used by the industry.

21.8.2 Industrial Inorganic Chemicals

Industrial inorganic chemicals represents a diverse group of products, including pigments, acids, salts, activated carbons, phosphorus, and sulfur (chlorines, alkalis, and industrial gases are inorganic; they are treated as separate industry groupings). The inorganic chemical industry accounts for about 25% of all chemical products, supplying raw materials to the automotive, paper, packaging, pharmaceuticals, and paint industries.

21.8.3 Manufactured Fibers

The manufactured fiber industry converts polymers such as nylon, acrylonitrile, polyester, polyurethane, cellulose, and cellulose acetate into four primary types of fiber: staple fiber, filament, monofilament, and tow. These products are, in turn, used as raw materials by the textile, apparel, and cigarette industries. The textile industry is the largest industrial consumer of manufactured fibers. Machine-drive applications account for 54% of total electricity use. Energy accounts for between 10% and 18% of the total cost of goods.

In addition to being energy-intensive, the manufactured fiber industry requires highly reliable power. The nature of the manufacturing process makes any interruption in the product flow costly. Since fibers are continuously spun, any disturbance in machine speed or temperature can severely impact product quality. Unexpected downtime can create costly, time-consuming cleanups. Manufactured fiber facilities typically operate 24 h per day, 365 days per year to avoid the cost of restarting the processes. Consequently, power reliability and power quality are high priorities for the industry. Similarly, the industry uses a very conservative approach to investments in electrical equipment.

21.9 THE PULP-AND-PAPER INDUSTRY

21.9.1 Industry Organization

This industry is basically organized into (1) pulp mills and (2) paper and paperboard mills. The pulp-and-paper industry includes the manufacture of pulp from wood products, the production of paper and paperboard from wood pulp, and the conversion of bulk paper and board to finished products. It is sometimes considered part of the larger forest products industry, which includes the agricultural activities of tree farming, as well the conversion of the trees into lumber and wood products.

21.9.2 Pulp Mills

The pulping industry includes the manufacture of wood pulp, which is the input for the entire paper industry. Most of the pulp produced in the United States is for internal use in paper production, but 10% to 15% of the total pulp produced is sold on the open market. Types of pulp include bleached kraft, unbleached sulfite, and thermomechanical products. The “type” refers to the pulp manufacturing process. Pulp types are typically destined for a specific market, such as the use of bleached kraft pulp in higher-quality printing and writing papers. Chemical pulp accounts for approximately 90% of U.S. manufactured wood pulp and is based mostly on the kraft process. In this process, wood chips are mixed with a caustic sulfite cooking liquor at temperatures of 176°C. The wood is then separated into individual fibers with limited mechanical agitation. When the resulting pulp is washed, the waste liquid is processed in a recovery boiler. This boiler generates steam for both process use and power production, and the pulp reduction chemicals are also partially recovered for reuse. Mechanical pulping is very electrically intensive, and essentially applies heat and pressure to convert wood to pulp. Mechanical pulping processes use 1400 to 1700 kWh per ton of pulp produced.

21.9.3 Paper and Paperboard Mills

This industry includes the production of paper, paper products, and packaging materials. The paper industry companies are typically vertically integrated and incorporate most elements of forest products in their businesses. Environmental pressures have increased for the industry since the late 1980s, as in the treatment of the low levels of dioxins in paper-mill sludges. The “cluster rule,” passed on April 15, 1998, regulates hazardous air pollutants and chlorinated organics (mostly phenolics). A focus of environmental concern is the continued use of bleaching technology that employs chlorine dioxide in the process. The chlorine dioxide is converted to sodium chlorate with the release of chlorine as a by-product. Mills are now introducing various control measures to deal with this issue.

Papermaking consists of stock preparation and formation of the final paper product in the paper machine. The primary step in stock preparation is refining the cellulose fibers in the pulp to facilitate good fiber-to-fiber bonding. The paper machine removes water from the pulp slurry, proceeding through processes of forming, pressing, and drying. To give an indication of the amount of water removal required in this process, approximately 100,000 gal of water is extracted for each ton of dry paper produced.

Stock preparation and refining requires 1 to 2 million Btu of thermal energy and 150 to 400 kWh of electricity per ton of paper processed. Paper refining requires 6 to 12 million Btu of thermal energy and 250 to 400 kWh of electricity per ton of paper processed. A newer technique of water removal—impulse drying—promises to improve overall efficiency with a lowering of thermal energy needs and an increase in electricity demand.

21.9.4 Power Distribution System

Mills typically use both 480- and 600-V systems for the lower voltage level, although 480 V is predominant. The mill may have its own substation, with distribution system higher voltages at 2400 to 15,000. Most large mills will have multiple 3-phase system voltages at levels including 480, 2400, 4160, or 13,800. Radial distributions are usually preferred because of their simplicity and lower cost.

21.10 DISTRIBUTED GENERATION

Distributed generation refers to small electric generating units located close to load centers. It encompasses onsite generation, self-generation, cogeneration, and any other small-scale power generation that is not considered central-station power. Distributed-generation projects are undertaken by end-use customers, electric utilities, gas utilities, power marketers, and other third parties.

The combination of electric utility deregulation, emerging generation technologies, and the growing worldwide demand for power has renewed interest in distributed generation. Electric utility industries are being deregulated in countries around the world. At the same time, new generation technologies such as fuel cells and microturbines are being commercialized, while conventional small-scale power generation technologies such as reciprocating engines and combustion turbines continue to make evolutionary improvements in performance. At the same time, worldwide demand for electric power has never been greater, and continues to grow, in both developed and developing countries. The combination of these three factors has led to a greatly increased interest in distributed generation.

21.10.1 Why Distributed Generation Is Used

Distributed generation is used for the following traditional applications:

- *Baseload power*, where the unit operates at a high-load factor throughout the year—usually the unit is operated as many hours as possible
- *Intermediate power*, where the unit operates during a specific period during the day, such as 9:00 A.M. to 6:00 P.M., during a specific seasonal or some other time period—usually 500 to 2000 h during the year
- *Peak shaving*, in which the unit operates only during the site's peak electricity demand or during peak electricity price periods—usually less than 500 h per year
- *Cogeneration* where the unit operates for a majority of the time during the year, and supplies both electricity and thermal energy to a site
- *Emergency/backup power*, where the unit is configured to supply power to the site in the event of a grid outage

In addition, a number of new niche applications for distributed generation have emerged, including

- *Premium power*—the unit supplies high power quality, free of interruptions, sags, surges, and spikes.
- *Green power*—the unit supplies power while generating low or zero emissions of pollution.
- *Power used as a hedge by power marketer*— in a deregulated electricity marketplace, strategically located small-scale power generation can be used as a source of power to fulfill contracts when the spot market price of electricity is high.
- *Remote power*—power is supplied where no distribution lines are available.

Various early adopters are currently using distributed generation for a number of reasons. Some use distributed generation purely on the basis of energy economics (distributed generation is cheaper for them than purchasing electricity from the grid). Others use small-scale onsite power generation because of the other benefits, such as increased reliability.

21.10.2 Distributed-Generation Technologies

A number of different technologies are available for distributed generation. Some of these are proven, mature technologies that have been used for decades. Others have been commercialized and have entered the marketplace only recently. Each is described below.

Reciprocating Engines. Otto and diesel cycle reciprocating engines were first developed in the late nineteenth century. They have gained widespread acceptance in almost every sector of the economy, and are used for applications varying from fractional-horsepower units used for small handheld tools to enormous 60-MW baseload electric power plants. Designs have been undergoing evolutionary changes and continue to improve in terms of efficiency, emissions, and other parameters.

For distributed-generation applications, there are two main types of reciprocating engines: Otto (spark ignition) and diesel (compression ignition). For most distributed-generation applications, these engines are of the four-stroke type, and use a piston that reciprocates in cylinders bore with the following cycles: (1) intake, (2) compression, (3) combustion, and (4) exhaust.

The piston starts at the top, the intake valve opens, and the piston moves down to let the engine take in a cylinder full of air and fuel during the intake stroke. Then the piston moves back up to compress this fuel/air mixture. Compression makes the explosion more powerful. When the piston reaches the top of its stroke, the spark plug emits a spark to ignite the fuel (in a diesel engine, the fuel is ignited by the compression alone). The fuel charge in the cylinder explodes, driving the piston down. Once the piston hits the bottom of its stroke the exhaust valve opens and the exhaust leaves the cylinder to go out the tailpipe. Now the engine is ready for the next cycle, so it takes in another charge of air and fuel.

Reciprocating engines are manufactured all over the world. They are currently being used in many distributed-generation applications, for primary power, intermediate power, peak shaving, and cogeneration. They are also used widely for emergency/backup power. They have a fairly low capital cost and reasonable electric efficiency, especially larger, low-speed units. For cogeneration applications, some low-quality steam can be produced, but most applications are for hot water.

Turbines. Combustion turbines are a widely used distributed-generation technology. They range in size from about 500 kW up to large utility-sized units of over 100 MW. Most of the smaller ones (less than 15 MW) are derived from aircraft engines; most of the larger ones are specifically designed for power generation. Combustion turbines are a proven technology that has been used for onsite power generation for many decades.

Combustion turbines consist of a compressor, a combustor, a turbine, and a generator. The compressors and turbines are typically multistage axial-flow designs, and somewhat resemble steam-turbine configurations.

Combustion turbines are used primarily for industrial and large commercial-sector cogeneration. They are also sometimes used for noncogeneration applications, and sometimes smaller units (usually less than 5 MW) are used for backup power. High-quality steam can be produced. Combustion turbines can be run on almost any gaseous or liquid fuel. Electric efficiency is usually poor (less than 35%, but overall efficiency in good cogeneration applications can be as high as 90%). At the time of writing, new combustion-turbine designs, utilizing technologies such as recuperators and ceramic components, with electric efficiencies of over 40%, are expected to enter the marketplace soon.

Microturbines. Microturbines are an emerging class of small-scale power generation technology in the 25- to 300-kW size range. The basic technology used in microturbines is derived from aircraft auxiliary power systems and diesel-engine turbochargers. A number of companies are currently field-testing demonstration units, and commercial deliveries have already begun. Microturbines consist of a compressor, a combustor, a turbine, and a generator. The compressors and turbines are typically radial-flow designs, and look much like automotive engine turbochargers. Most designs are single-shaft, and use a high-speed permanent-magnet generator that uses an inverter to produce ac power.

A number of different microturbine designs and configurations have been tested by manufacturers. The following are some fundamental design and configuration considerations:

Recuperation. Recuperators are air-to-air heat exchangers that use a microturbine's hot exhaust gases to heat the combustion inlet air after it has been compressed. Recuperators are key to the electrical efficiency of microturbines.

Single-shaft with high-speed permanent-magnet generator and inverter versus split-shaft with reduction gearbox and 60-Hz induction generator. Two different ways of producing ac power with microturbines are currently being evaluated in the demonstration units. The first and more common uses a single shaft with a high-speed permanent-magnet generator spinning at the same speed as the turbine. This generator produces very high-frequency ac power that must be converted to 60 Hz using an inverter. The second design uses a two-shaft configuration with a reduction gearbox and a 2-pole, 3600-r/min induction generator that directly produces 60 Hz of power.

Air-bearing versus oil-lubricated. Microturbines are high-speed ($\geq 40,000$ r/min) rotating equipment that require high-reliability bearing systems. Two different configurations are currently being used. The first uses air bearings with a compliant foil system that requires no oil lubricant. The second uses a pressurized lube-oil system with a pump, similar to that used by an automobile engine.

Fuel-cell hybrids. Power generation systems utilizing fuel cells combined with microturbines are also being developed by several manufacturers. These systems typically run the hot gas produced by fuel cells through a microturbine to generate additional electricity. Hybrid systems are predicted to have exceptionally high electric efficiencies ($\geq 60\%$).

Gasifiers. Gasifiers produce gaseous fuel from solids, such as coal and biomass. Small-scale gasifiers for use with microturbines are still in the development stage. Gasifiers could help microturbines gain wider acceptance, especially in international markets.

With recuperation, microturbine efficiency is projected in the 26% to 30% (LHV) range. The overall efficiency is projected at 65%. Overall efficiencies may reach 85%, similar to larger turbines. Microturbines can run on natural gas, diesel, gasoline, kerosene, naphtha, methanol, ethanol, alcohol, propane, JP-8 Flair Gas, and other gases with heating values over 500 Btu/lb.

Fuel Cells. Fuel cells are an emerging class of small-scale power generation technology in the ≥ 25 - to 1000-kW size range. The first fuel cells were developed in 1839 by Sir William Grove, although they were not used as practical generators of electricity until the 1960s, when the U.S. space program chose fuel cells for the *Gemini* and *Apollo* spacecraft.

There are a number of fuel-cell types and configurations, but they all use the same basic principle. A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water, and heat. Hydrogen fuel is fed into the anode of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Encouraged by a catalyst, the hydrogen atom splits into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte. The electrons create a separate current that can be utilized before they return to the cathode to be reunited with the hydrogen and oxygen in a molecule of water. A fuel-cell system usually includes a “fuel reformer” that can utilize the hydrogen from any hydrocarbon fuel—from natural gas to methanol, and even gasoline.

Other Technologies. Other technologies that fall under the distributed-generation umbrella include renewables such as photovoltaic (PV) and wind power. PV technologies convert sunlight directly to electric power. Current PV technologies have very high capital costs, but they continue to improve. Wind-power systems use turbines turned by wind to provide torque to a shaft that turns a generator. These technologies also continue to improve, and now can provide electricity at competitive rates, although they obviously operate only under the proper atmospheric conditions.

21.11 ELECTRIC MELTING

21.11.1 Process Overview

Electric Melting Applications. Electricity has been used extensively for industrial process melting applications since the early 1960s, including iron, steel, nonferrous metals, and glass. The most important applications of electric melting are

1. Melting and refining of steel
2. Melting, holding, and casting of most metals, including iron, steel, and nonferrous metals
3. Melting, refining, forming, and annealing of glass

Glass Melting. Electricity has been used in glass production to melt, refine, form, and anneal glass to the desired properties for use in containers, flat glass, pressed and blown glass, and glass fibers. Applications for electrically melting glass were limited until the mid-1950s, and since then its use in either all-electric furnaces or electrically boosted melting has grown substantially.

TABLE 21-1 Melting Points of Metals

Metal	Melting point	
	°C	°F
Group 1		
Tin	232	450
Bismuth	271	520
Cadmium	321	610
Lead	327	621
Zinc	420	788
Antimony	630	1166
Magnesium	651	1204
Aluminum	659	1218
Group 2		
Silver	961	1761
Copper	1083	1981
Nickel	1452	2646
Cobalt	1480	2696
Iron	1530	2786

Technology Applications. The following sections discuss four technologies used for electric melting applications.

Metal melting includes, in addition to the change of state, the further heating of the metal to a specified temperature, known as the “pouring temperature,” if the metal is to be poured into a mold or the “working temperature” if the metal is to be used for coating, as in galvanizing, or as a liquid heating bath.

Table 21-1 refers to melting service. An alloy belongs in a group of this table to which its major component belongs. The melting-temperature range of an alloy must be obtained from the constitution diagram of a system to which the alloy belongs.

The pouring temperatures of nonferrous metals and alloys range from 100 to 200°C (180 to 360°F) above the melting point. They vary for each metal or alloy with the type of load and the size and type of casting according to the purpose for which the casting is to be used.

Volatilization occurs. In melting metals there is a certain loss by volatilization. This loss of metal is usually negligible except for charges which contain a high percentage of zinc. Another consideration is the poisonous nature of zinc fumes.

Stirring an alloy while it is in the molten state is often necessary to prevent segregation. Stirring is also an aid in bringing about equalization of temperature and is a safeguard against overheating in the surface of the molten mass.

Automatic stirring can be obtained with suitable induction coils or by the use of an induction furnace.

21.11.2 Melting Pots

The melting of the soft metals, or group 1 (see Table 21-1), and their alloys is within the range of the 80 Ni-20 Cr alloy-resistor heating equipment. Containers for these materials are designated as melting pots, solder pots, lead pots, galvanizing kettles, tanks, etc.

Melting pots are made of cast iron or steel and of various nonferrous alloys. The selection of the material for the pot depends on the temperature of the molten metal and the possible reactions of that metal with the material of the pot.

Open-top pots are used in which the molten metal is removed by dipping or pumping and into which metal is dipped for coating. A greater depth than is necessary for the service is desirable as an aid to temperature recovery when cold metal is added.

Closed-top pots are advantageous in reducing the heat loss from the molten-metal surface and in reducing oxidation. Also, space can be provided for a protective atmosphere. Discharge of the molten metal by gas pressure, for example, steam, is incorporated in some designs.

The heat insulation of a metal melting pot should be sufficient to limit the outside surface temperature to a safe value. Otherwise, insulation is a matter of economy. As a rule, a layer of refractory material is unnecessary for temperatures below 600°C (1112°F). A refractory layer is useful as an aid in maintaining an even metal temperature.

Heat loss occurs. The rates of heat loss can be reduced by a layer of insulating material in granular or gaseous form, for example, charcoal or diatomite on the surface of the metal or sulfur dioxide. This layer also reduces oxidation of the metal. When using gaseous layers, adequate ventilation must be provided.

A *cast-in unit* is a self-contained heating unit embedded by casting in a mass of gray iron. This unit is designed for metal-melting services up to 510°C (950°F). The unit is applicable to the melting of all the soft metals with the exception of aluminum and zinc, exceptions because of their alloying action with iron. The rating of the unit should be on the open-air basis.

External heating units supplied to a melting pot should be rated on the basis of 20 to 20 W/in² of the side surface of the container. This design of melting pot is suitable for molten-metal temperatures up to 898°C (1650°F).

The temperature-regulating equipment of melting pots is the same as used for resistor ovens and furnaces. As a rule, small melting pots—say, 5 kW and below—have only manual control by a two- or three-point switch.

The melting rate of a melting pot is measured by the time required for the charge of molten metal to regain the pouring or working temperature after the addition of a quantity of cold metal. For example, if 100 lb of cold metal is added and the metal in the pot regains its temperature within 10 min, the melting rate for that metal is $100 \times 6 = 600$ lb/h.

The kilowatts rating of a melting pot is based on the required rate of melting a given metal or alloy. For melting quantities of metal, for example, for castings, the kilowatts rating should be no less than the rate of heat input to the metal plus the rate of heat loss. For melting for coating work, for example, galvanizing, the kilowatts capacity needed is the sum of the capacities required for melting, for heating the base material, and for the rate of heat loss. As a rule, some additional capacity is installed to accelerate heating up and to prevent too large a drop in temperature when cold metal is added. The operating efficiency of the melting range is not affected by its kilowatts rating.

Metals of group 2 and their alloys require either the arc furnace or the induction furnace for melting. Brass and steel are the major alloys of this group.

21.11.3 Arc Furnaces

The two types of arc furnace in common use are (1) the 3-phase furnace and (2) the single-phase furnace. The general field of the 3-phase furnace is the production of alloy steels; that of the single-phase furnace, the production of nonferrous alloys. Both types of furnace can be used for the manufacture of high-quality gray-iron castings. However, the use of large-size induction coreless and core-type furnaces may be preferable.

Three-Phase Arc Furnace. Standard sizes of arc furnaces range from 250 to 80,000 kVA; loading range, 500 lb to 250 tons. Sizes 1000 to 5000 kVA predominate.

The chamber is a steel bowl with a refractory lining. The hearth is a shallow bowl formed in the bottom lining. The roof is a removable dome-shape refractory structure carried on a steel roof ring. The roof has three round ports in equilateral triangular arrangement through which vertical carbon or graphite electrodes travel. Each electrode is carried on a winch-and-rope system, motor-driven.

Refractories. The chemical nature of the slag, acid or basic, determines the required chemical nature of the lining of the hearth and sidewall of the chamber up to a few inches above the top surface line of the slag, that is, an acid refractory (silica) for acid slags, and a basic refractory (magnesia) for basic slags. The roof is usually made of silica brick. Silica has a tendency to spoil during heating and cooling, and furnaces which are in intermittent use often have roofs made of fire-clay brick.

Temperature. The operating temperature of the chamber is limited by the softening point of the refractory, particularly that of the roof, where there is a concentration of heat. A refractory material can be operated with the temperature of its inner face close to its softening point provided that the outer face is exposed to the open air, thus permitting a flow of heat through the refractory body. A temperature gradient is thus established in the refractory so that if its thickness is correctly related to its thermal conductivity the mean temperature of the refractory body will not be high enough to impair its strength materially.

The temperature of molten steels is around 1600°C (2912°F). The melting point of silica is 1713°C (3115°F), but the softening point of a silica refractory is somewhat lower because of impurities in the refractory body. Hence, in a steel melting furnace the temperature of the inner face of the refractory lining is too high to permit the use of heat insulation. Even a thick coat of dust on the roof of the melting furnace is undesirable.

The designation for a 3-phase arc furnace may be given in terms of the holding capacity, the shell diameter, the pouring capacity, the melting rate, or a combination of these. A given diameter of shell can be attached to a range of ratings by varying the thickness of the refractory linings. Sizes are given in Table 21-2.

Charges. The 3-phase arc furnace is primarily a scrap-metal-conversion unit. The two types of furnace with respect to the method of charging are (1) the door-charge type and (2) the top-charge

TABLE 21-2 Representative Sizes of 3-Phase Arc Furnaces in General Use

Shell diameter	Normal charge, lb	Transformer rating, kVA	Single slag heats, lb/h
4 ft	800–1,000	250–350	500
4 ft 6 in	1,200–1,500	350–500	900
5 ft	1,500–2,000	500–750	1,300
6 ft	3,000–4,000	750–1000	2,000
7 ft	5,000–6,000	1000–1500	3,000
8 ft	7,000–9,000	1500–2000	4,500
9 ft	10,000–12,000	2000–3000	6,000
10 ft	16,000–20,000	2500–3000	10,000

Note: 1 ft = 0.3048 m; 1 lb = 0.4536 kg.

TABLE 21-3 Approximate Current-Carrying Capacities of Graphite Electrodes for Arc Furnaces

Nominal diameter, in	Amperes	Nominal diameter, in	Amperes
2	600–1000	9	6,400–10,800
2½	800–1500	10	7,800–12,500
3	1200–2100	12	11,300–17,000
4	1800–3000	14	15,400–21,500
5½	2300–4100	16	20,100–26,100
6	3100–5400	17	22,700–27,400
7	4200–6900	18	25,500–30,500
8	5500–9000	20	28,300–34,600

Note: 1 in = 25.4 mm.

type. Depending on the character of the scrap, hand charging and chute charging are the usual methods for small furnaces. Large furnace installations are often equipped with side-door-charging machines. Top charging is favored for medium-size furnaces. In this method the roof of the furnace is removed, and a complete charge is placed in the chamber by a drop bucket handled by an overhead crane. This is both a time-saving and a labor-saving method. The charging time is only a few minutes, for example, a reduction from 30 to 5 min. Top charging has the other advantage of a full chamber and a lower heat loss during the charging.

Some 3-phase arc furnaces are used for refining service only. Molten metal from an open-hearth furnace, Bessemer converter, or cupola is the charge.

The weight of scrap metal varies with the degree of its subdivision. The weight of charge that can be placed in a given furnace depends on the kind of scrap. If sufficient scrap metal cannot be placed in the furnace initially to form the weight of molten metal desired, additional quantities can be added later in the heat cycle. This practice affects adversely to some extent both the operating efficiency and the consumption of electrodes.

Electrodes. The arc in each phase is maintained between the tip of the electrode of that phase and the charge (bath after the molten state is reached). The charge thus serves as a common electrode for the three arcs and makes a connection of the 3-phase circuit at that point. The designation “direct-arc furnace” refers to this arrangement.

The trend is toward the general use of graphite electrodes. Carbon electrodes are preferred in some cases. Standard sizes in the corresponding current ratings are given in Tables 21-3 and 21-4.

The consumption of electrodes is caused largely by volatilization and burning. There is some breakage. Graphite begins to oxidize at about 600°C; carbon, at 400°C. Under average conditions the consumption of graphite electrodes is about one-half that of the carbon electrodes. Average values for melting service, pounds of electrodes per ton of metal melted, are graphite 4 to 10; carbon 8 to 15. The corresponding consumption in melting refining service is about 10 lb for graphite and 18 lb for carbon.

Voltamperage. The voltampere characteristic of the arc is negative and a stabilizing element is necessary for circuit stability. Reactance also serves to limit the current in the circuit when an

TABLE 21-4 Approximate Current-Carrying Capacities of Carbon Electrodes for Arc Furnaces

Nominal diameter, in	Amperes	Nominal diameter, in	Amperes
8	2,000–3,000	20	11,000–17,300
10	3,000–4,800	24	15,800–24,800
12	4,500–6,800	30	24,700–35,300
14	5,400–8,500	35	28,800–38,400
17	7,900–12,500	40	37,700–50,200

Note: 1 in = 25.4 mm.

electrode touches the charge. This reactance is a total reactance of the circuit from the furnace terminals to the point in the power system where the voltage is held constant. Thus a furnace at the end of a long feeder is a different problem from a furnace installed adjacent to a large substation.

The operation of an arc furnace is dependent on the stabilizing element of the circuit only to the extent of ensuring continuity of operation. The limitation of current fluctuations is a problem of power service and is individual for each location. The resistance of the circuit is also a factor, and the actual value of the short-circuit current will be less than that indicated.

Circuit Characteristics. The arc-furnace circuit (containing resistance and reactance) is operated at constant voltage and supplies the unity power-factor load, the arc or arcs. The maximum power of the circuit occurs at 0.707 power factor. The maximum power in the arc occurs at a higher power factor of the circuit, a value dependent on the constant of the circuit.

Electrical Apparatus. The rating of the electrical equipment of a 3-phase arc-furnace installation varies for a given size furnace for the class of service and in some cases according to the power-service conditions. The electrical equipment includes

1. A variable-ratio power transformer
2. Reactors if required
3. An automatic current regulator
4. A control panel for the operator
5. Electrode motors and tilting motors
6. A main-line circuit breaker and disconnecting switches

Transformers. The features which distinguish the arc-furnace transformer from the conventional power transformer are (1) individual service, (2) no requirement of regulation, and (3) a wide range of comparatively low secondary voltages and correspondingly high secondary currents.

Reactance. There are no criteria for stability in current limitations in arc-furnace circuits and hence no standard values of reactance in these circuits. As a rule, 40% to 60% reactance is satisfactory.

The inherent reactance in the circuit of a large furnace—500 kVA and larger—may be, and usually is, sufficient for the need. As the secondary voltage is fixed by conditions other than the kVA rating of the circuit, the smaller installations require more or less supplemental reactance.

The normal reactance of 60-Hz furnace transformers ranges from 5% to 7%. Reactance values higher or lower in each case, within certain limits, than the range noted can be obtained by design but may entail a sacrifice one way or another in the design of the transformer. Hence it is considered better practice to use a normal design of transformer and to add supplemental reactance, if needed, by reactors.

Reactors should have a number of taps for adjustment after installation. The transformer taps and reactor taps are connected into a common terminal board arranged so that any combination of transformer taps and reactor taps can be made for each of the selected operating voltages.

The diagram in Fig. 21-6 illustrates a tap arrangement and switching arrangement for operating voltages and the use of reactor windings for both the delta and the Y connection.

An example is the connection of one installation given in the table.

Automatic Current Regulator. A change in current causes a change in the power of an arc-furnace circuit. Within the limits of circuit stability the current with a given applied voltage can be changed by changing the

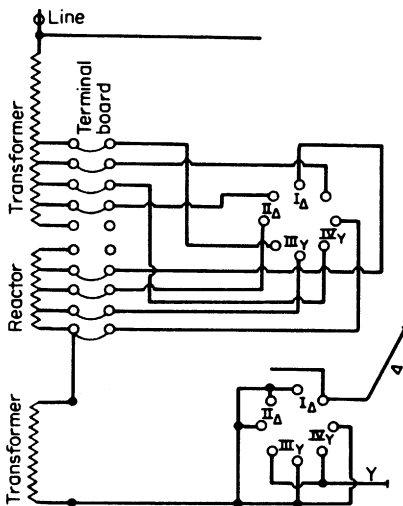


FIGURE 21-6 Diagram for four operating voltages, one phase only of a 3-phase transformer.

length of the arc. This is the principle of the power regulation of arc furnaces.

The intermittent-type current regulator, which operates within preset limits of current variation, has been superseded almost entirely by the continuous-type current regulator.

A simplified diagram, one phase only of the continuous-type regulator, is shown in Fig. 21-7. The principle of operation is the opposition of a voltage B derived from the circuit of the arc by a reference voltage A. The resultant value of these two voltages determines the polarity of the generator that drives the electrode motor. Thus the length of the arc—and correspondingly the current in the arc—is maintained at a predetermined value.

Each phase in the 3-phase circuit is regulated independently. However, because of the common electrode, the charge, or both, the three elements of a 3-phase regulator work together for the maintenance of equal currents in the three circuits of the power system.

The automatic regulator performs three other functions:

1. The feeding of the electrodes at the rate of consumption
2. The removal of partial short circuits caused by the electrodes coming into contact with the charge
3. The protection of the equipment in case of a failure of the power supply

Operator's Panel. The standard equipment consists of three ammeters, a polyphase wattmeter, a voltmeter, and the necessary rheostats and switches for the operation of the furnace.

The Electrode Drive. This is a reversing service—rapid at certain times—and a motor with a low WR^2 effect is desirable.

The Main-Line Circuit Breaker. This serves both as a protective device and as a switch. The switching service rate is many times per day. In normal operation the arc circuit is opened by raising the electrodes so that the circuit breaker opens the magnetizing part of the power transformer.

All changing of taps is done with a main-line circuit breaker open (no-load tap changing). The tap-changing switch is interlocked with the circuit breaker to prevent incorrect operation. As a rule the tap-changing switch is mounted inside the tank in 3-phase transformers and outside when three single-phase units are used. The tap-changing switch can be motor-operated or hand-operated; the former is the more general practice.

Single-Phase Arc Furnace. The most common single-phase arc furnace is the automatic rocking furnace. This furnace is used extensively for melting both ferrous and nonferrous metals and alloys. Standard sizes extend up to and include 600-kW ratings for melting 4000 lb of cold steel scrap in 90 min.

The load characteristics of a single-phase arc furnace are similar to those of 3-phase arc furnaces. However, as there is no arc between an electrode and the charge, the initial performance of the single-phase furnace is somewhat better than that of the 3-phase arc furnace. The average power factor of the single-phase furnace is 70% to 80%.

Electrical equipment for single-phase arc furnaces is similar to that for 3-phase arc furnaces. Usually only one operating voltage is used.

Gray iron with uniform structure and high engineering properties, namely, tensile, bending, shearing, and impact strength, is produced in arc furnaces. The method of production involves superheating the iron after melting to about 1600°C (2912°F) and holding it at the elevated

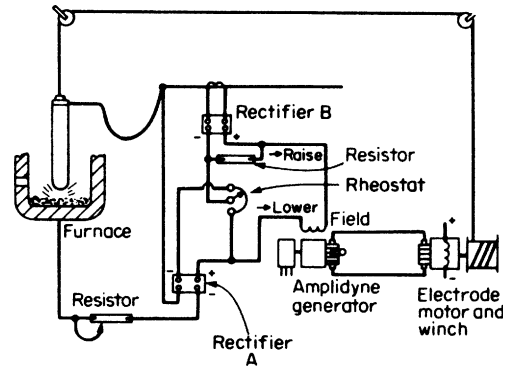


FIGURE 21-7 Simplified circuit diagram of continuous-type automatic current regulator for a 3-phase arc furnace (single phase only).

temperature for a brief period of time. Gray irons with the tensile strength of 40,000 lb/in² are produced regularly by this method.

21.11.4 Induction Furnaces

Two types of metal-melting furnace that embody the induction principle are the coreless furnace, which can be used in operation from frequencies of main-line 60 Hz up to many hundreds of kilocycles (the frequency generally depends on the size of the furnace) and the channel furnace, most generally operated from main-line frequencies, principally 60 Hz.

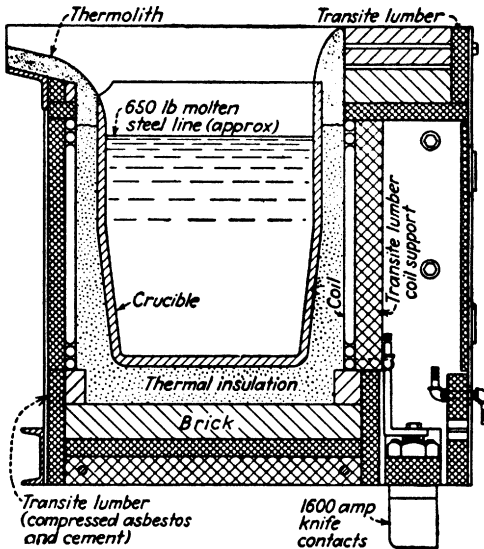


FIGURE 21-8 Coreless induction furnace.

ing capacity. Over 500-lb capacity rammed linings are employed rather than preformed crucibles. The preformed crucibles are generally used for nonferrous melting.

Standard sizes for steel melting furnaces are 50 up to 60,000 lb. These are often listed in the ratings of 100-lb capacity, 200, 300, 600, 1000, 1500, 2000, 4000, 8000, 10,000, 15,000, 20,000, and 40,000-lb capacity, plus the various intermediate sizes.

Features of operation peculiar to this type of melting furnace are that

1. The refractory container makes necessary a large air gap (loose coupling), with consequent low power factor, 20% to 30%.
2. The charge is cold scrap metal. Thus, initially, the secondary circuit is a current path through a variety of shapes and dimensions of pieces, and contact resistance is a large part of the total resistance. The charge becomes homogeneous as the metal melts, shrinks in height, and thus decreases the coupling of the circuit. At this time, cold metal may or may not be added to the charge. It is a common practice after the first melt to maintain a molten heel in the furnace to expedite the melting of the second load.

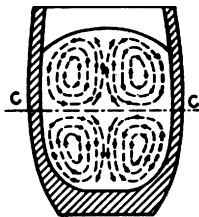


FIGURE 21-9 The stirring effect in a mass of molten metal being heated by induced currents.

3. With charges of magnetic material the effect of the magnetic property is pronounced at the start of the heat cycle.
4. Stirring of the molten metal, as indicated by Fig. 21-9, is characteristic of this furnace. This movement of the bath has much metallurgical significance in the production of homogeneous alloys. The movement is often desirable and can be regulated to a certain extent by the frequency selected for the size furnace involved.

The Coreless Induction Furnace. The general design of this furnace is shown in Fig. 21-8. The assembly consists of three main parts: (1) the primary coil, (2) the refractory container, and (3) the frame, which includes supports and tilting mechanism.

The distinctive feature of this furnace in common with other assemblies for induction heating is the absence of a continuous iron path for the magnetic flux. However, iron laminations are frequently used on the larger sizes, and particularly for line-frequency furnaces, to reduce the reactance for the flux on the back or outside of the furnace. Another feature for comparison with other types of melting furnace is the small quantity of refractory material in the construction.

Standard preformed crucibles are used for the smaller furnaces, up to about 500-lb holding capacity.

The characteristics of charges vary widely, but the general practice is to vary the capacitance on the circuit during the heat cycle to maintain approximately unity power factor.

Frequency. The primary technical factor in the selection of frequency for a metal-melting furnace is the desired degree of stirring of the molten metal for the size of furnace required. This stirring effect is proportional to the square of the ampere-turns and inversely proportional to the frequency. For a given power value, the current decreases and the voltage increases with increase of frequency.

A second consideration is the fineness of the scrap metal of the charge. If the pieces are very small, there may be difficulty in starting the melting of a cold charge. The frequency must be high enough in a given case to give an electrical efficiency high enough for starting. These conditions and the economics of the service early led to the adoption in this country of 960 Hz for steel-melting furnaces, 100 kW and above, and 3000 Hz for smaller furnaces. As a rule these frequencies are also suitable for melting nonferrous charges. Various frequencies are used for laboratory furnaces. In general industrial practice the trend is to use 60 Hz where large-tonnage furnaces are being used.

Service. The coreless induction furnace is primarily a metal-melting unit. An important use of this furnace is the production of carbon ferrous alloys. The refining of steel, that is, the removal of phosphorus and sulfur, in this furnace has not been developed to a fine art. The deoxidation of the melt, for example, by the addition of aluminum just before pouring, is not here classed as refining. Various special services are duplexing steel, vacuum melting, heating of charges of nonconducting material (with or without melting) by the use of conducting crucibles, etc.

Performance. The melting rate of a furnace, and consequently the power input, is determined in each case by the rate at which the molten metal can be used. Heat cycles of $\frac{1}{2}$ h for small furnaces, 1 h for medium-sized furnaces, and $1\frac{1}{2}$ to 2 h or more for large furnaces represent typical practice.

Energy Consumption. This varies for a given material with the size of the furnace, the melting rate, and the idle time between heats. Representative values are 330 kWh/ton (2000 lb) for copper 500 kWh/ton for gray iron, and 600 kWh/ton (2000 lb) for steel. These figures are lower with larger furnaces in continuous operation and somewhat higher with small units and infrequent service.

The Channel (Core-Type) Furnace. The basic feature of this furnace is a single-turn loop of molten metal below and connected to the bath serving as a secondary circuit. A conventional laminated steel core and primary winding complete the transformer feature.

The heat is developed in the loop of molten metal below the body of the charge. Electrodynamic action causes motion of the metal in the loop as indicated. This movement serves to transfer the heat and so stir the molten metal in the chamber above the loop.

Starting the furnace requires sufficient molten metal to close the secondary circuit. In changing from the metal or alloy to another, the furnace must be emptied. For day-to-day melting of the same metal or alloy—the usual practice—the charge, or a portion of the charge, is held molten overnight by using a below-normal voltage.

The V-shaped loop furnace is designed for melting the heavy nonferrous metals and alloys. It is used widely for melting brass. With these metals the slags, or nonmetallic particles, in the melt are much lighter than the metal, so that they tend to float on the surface of the bath and do not interfere with the circulation of the metal in the loop of the secondary circuit.

Standard sizes on these furnaces range from 60 to 1000 kW on single-phase, 60 Hz in the United States, and for standard voltages up to 600 V inclusive.

A design of the channel furnace for melting aluminum and its alloys embodies two or more vertical channels below the bath and connected to the bottom by horizontal channels of larger cross section. The slag particles of the lighter metals have about the same specific gravity or are heavier than the molten metal. Such particles tend to accumulate in the channel of the secondary circuit. The design of the channel noted above provides for its easy cleaning from time to time while the furnace is in operation.

Power and power factor of the channel furnace with constant applied voltage vary with the resistivity of the metal in the loop that forms the secondary circuit.

21.11.5 Resistance Furnaces

Resistance furnaces have a temperature range of 1500°C (2732°F) and above. This type of furnace is generally an open-top heating chamber with electrodes—movable or fixed—buried in the charge. Variations are furnaces with closed tops, furnaces with a resistor buried in the charge, etc.

The general service is heating charges of a refractory nature to bring about chemical reactions or changes in the physical structure of a material. Where the product is obtained by a chemical reaction, for example, the reduction of a metallic oxide, the term *smelting furnace* applies.

The length and cross-sectional area of the path of the current through the charge are proportioned to suit the power characteristic of the material to be heated. Where the buried resistor is used, its design is based on similar considerations. In all cases the load is resistance, that is, the I^2R effect. In some cases where the charge forms a resistor, there may be arcing along the path of the current.

Glass applications require conventional fuel firing initially to melt the glass. Once molten, glass conducts electrically and can be processed using bottom or side electrodes.

There are no standard designs of resistance furnaces. Each application is an individual undertaking, and the furnace is assembled in place. The simplicity of the construction permits a wide range of designs and much latitude in dimensions.

Resistance furnaces are unity-power-factor loads, and the circuit is stable; that is, reactance is not needed as with other furnaces. However, there are reactances and resistances in the furnace conductors, and the circuit characteristics are the same as for arc-furnace circuits. The voltage is low, generally less than 250 V. The corresponding high-current values introduce problems of inductance in the leads to the furnace, particularly with 60-Hz power supply.

Furnaces with Movable Electrodes. There are stationary, vertical, cylindrical, or rectangular structures, single- or 3-phase (see Fig. 21-10). The latter is more common.

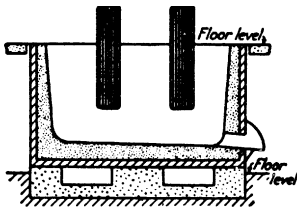


FIGURE 21-10 Open-type resistance furnace with movable electrodes (three electrodes for a 3-phase furnace).

The material of the charge, granular in form, is fed, more or less continuously, into open-top furnaces or through chutes into closed furnaces. The product, if molten, is discharged by tapping through a side, usually near the bottom. Vapor products pass out at the top or through the side openings in the chamber. If the product is solid, for example, fused magnesite, the batch method is used and the furnace is disassembled for removal of the product.

The regulation of movable-electrode furnaces is accomplished by electrode movements to hold constant current, as with arc furnaces. The load is fairly uniform, and the regulating duty is light. Either dc motors or ac motors can be used to drive the electrodes. Direct-current motors are more often employed because of the ease of speed adjustment and the superiority of dynamic braking.

Continuous operation at one voltage is general practice. Transformers for these furnaces have a number of taps in the primary windings for the selection of the secondary voltage to suit operating conditions, which may change from time to time.

Batch Furnaces with Fixed Electrodes. A horizontal rectangular chamber with an electrode at each end is typical construction where the current is passed through the charge.

Refractory materials have negative resistivity versus temperature coefficients. Hence, to maintain constant power in a batch furnace as the temperature of the charge rises, the applied voltage must be varied as expressed by Eq. (21-12) or (21-13). Accordingly the regulation of furnaces of this type is by voltage adjustments, either load-ratio control or no-load tap changing, the latter with or without an induction regulator for intermediate voltages. Generally manual operation is sufficient. Constant power is not the rule. In many cases the power input is varied to correspond to a prescribed heat cycle.

Some of the more common uses of resistance furnaces are for calcium carbide, ferroalloy, ferrosilicon, ferromanganese, ferrochromium silicomanganese, ferrotungsten, ferromolybdenum, silicone oxycarbide, graphite, fused alumina, fused magnesia, fused silica, zinc oxide, and pig-iron applications.

21.12 ELECTRIC HEATING

21.12.1 Principles of Heating

Material is heated for processing purposes either (1) in the open air or (2) protected from the air in a vacuum or a special gas chamber. In comparative terms, in open air the rate of heating is fast and the time short. With enclosures the rate of heating depends on the source. It may be fast; generally it is slow, however, and the time is long. The basic consideration in each case is the correlation of temperature and the time, dictated by the material to be heated and the results desired.

Electric heating has certain unique characteristics:

1. The precision of electric control is extended to the transfer of heat. Uniformity of temperature within a relatively narrow limit is readily attained.
2. Its development does not involve combustion.
3. There is no upper limit to the temperature obtainable except the ability of the materials to withstand heat.

The collateral merits of electric heat vary in value with the conditions in each case. The most important of these are

1. Application at the precise point needed
2. Flexibility, includes easy subdivision, freedom of location, and general adaptability
3. Good working conditions, cleanliness, quietness, ambient temperature minimally affected, etc.
4. Fast response
5. Safety

Heat-Process Engineering. The heating method for a particular process may be selected after consideration of two basic principles of industrial heating: (1) temperature and (2) mode of heat transfer. This narrows considerably the field from which a choice of the heating method should be made. Generally there is more than one possible method. Economic factors must then be taken into account. This, in addition to the relative capital, maintenance, and energy cost, includes a study of the collateral merits of methods that always have a bearing on the overall cost of production.

A convenient temperature classification is

Low temperature—up to 400°C (752°F)

Medium temperatures—400 to 1150°C (752 to 2102°F)

High temperatures—beyond 1150°C (2102°F) (see section on electric melting)

Heat energy is transferred by conduction, radiation, convection, high-density electromagnetic force, and concentrated electrostatic fields. The transfer can be obtained with a combination of these methods.

Heat conduction can take place in all three states of matter, that is, in solids, in liquids, and in gases. Thermal conductivity is defined as the quantity of heat which flows in unit time through unit

area of a plate of unit thickness having unit difference of temperature between its faces. There is no generally accepted combination of units for expressing thermal conductivity. Some of the more common combinations of units for this value are:

$$\begin{aligned} k &= \text{Btu/ft}^2 \cdot \text{h for 1-in length of path/}^\circ\text{F (British units)} \\ &= \text{cal/cm}^2 \cdot \text{s for 1-cm length of path/}^\circ\text{C (cgs units)} \\ &= \text{W/(in}^2) \cdot (1\text{-in length of path)} \cdot (^\circ\text{C}) \end{aligned}$$

TABLE 21-5 Thermal Conductivities k^*

Solids at or near room temperature	
Silver	2824
Copper	2661
Aluminum	1463
Zinc	769
Iron	467
Nickel	412
Marble	21
Ice	15
Porcelain	7
Chalk	7
Glass	5
Liquids at temperatures noted	
Water, 20°C	4.15
Glycerin, 9–15°C	1.85
Ethyl alcohol, 20°C	1.23
Petroleum, 13°C	1.03
Gases at temperatures noted	
Hydrogen, 100°C	1.00
Methane, 7–8°C	0.188
Air, 0°C	0.165
Ammonia gas, 0°C	0.130
Carbon dioxide, 0°C	0.090

*British units; divide by 2903 to obtain corresponding cgs values of k .

tion. If the area of the cross section of the path of heat flow varies along its length, the equation is applicable if the logarithmic mean area of the path is used.

For boundary surfaces that are not smooth curves, a shape factor S must be substituted for the term A/l in Eq. (21-1); thus

$$h_c = Sk_m t' \quad (21-2)$$

Two of the equations for the shape factor S are

1. Rectangular enclosures (Fig. 21-20):

$$S = \frac{A}{t} + 0.54 \sum l + 1.20t \quad (21-3)$$

where A = inside surface area, t = thickness of wall, and $\sum l$ = sum of length of all inside edges.

Values of k for various materials as published are not based on a common method of determination. Hence, agreement in thermal-conductivity data for a given material cannot be expected.

The thermal conductivity of a material is affected by temperature, in some cases increasing, in other cases decreasing with rising temperature. Values representative of the general order of the thermal conductivities of ordinary temperatures of the three states of matter are given in Table 21-5.

An arbitrary standard by which to judge the value of a material as a nonconductor of heat (heat insulator) is $k = 1$ (British unit).

The law of thermal conduction for a constant-temperature gradient is expressed thus:

$$h_c = \frac{Ak_m t'}{l} \quad (21-1)$$

where h_c = rate of heat transfer by conduction, A = area of cross section of path of heat flow, t' = temperature gradient, l = length of path, and k_m = mean value of thermal conductivity of material in which the temperature gradient is established for a given range of temperature.

Shape Factor. Equation (21-1) as written is applicable only to paths of uniform cross section.

2. Cylindrical enclosures (Fig. 21-21):

$$S = \frac{A}{t} + 0.54 \sum l + \frac{2\pi h}{2.30 \log (b/a)} \quad (21-4)$$

where A = inside area of top and bottom surfaces, t = thickness of wall, $\sum l$ = sum of lengths of inside top and bottom edges, h = inside height, b = outside diameter, and a = inside diameter.

Radiation. Radiation is a surface phenomenon. Surfaces emit and absorb radiant energy in various degrees, depending on the nature of the surface.

Average values of radiation and absorption coefficients are given in Table 21-6.

Solids for the most part are opaque to radiation; a notable exception is quartz. Liquids transmit radiation to some extent. Only two gases, water vapor and carbon dioxide, absorb radiation to any marked degree.

The rate of heat transfer by radiation under the conditions usual in heating practice is

$$h_r = \epsilon \times 3.68(T_0^4 - T_a^4) \times 10^{-11} \quad (\text{Celsius scale}) \quad (21-5)$$

$$h_r = \epsilon \times 0.35(T_0^4 - T_a^4) \times 10^{-11} \quad (\text{Fahrenheit scale}) \quad (21-6)$$

where h_r = watts per square inch, ϵ = absorption coefficient of receiving surface, T_0 = absolute temperature of emitting surface, and T_a = absolute temperature of absorbing surface.

Natural Convection. Natural convection is a transfer of heat to or from a surface by the movement of a fluid or gas when this movement is caused solely by a difference in fluid or gas density.

For natural convection in air

$$h_b = 11.70 \times t \times 1.25 \times 10^{-4} \quad (\text{Celsius scale}) \quad (21-7)$$

$$h_b = 6.50 \times t \times 1.25 \times 10^{-4} \quad (\text{Fahrenheit scale}) \quad (21-8)$$

TABLE 21-6 Average Values of Radiation (and Absorption) Coefficients

Material	ϵ radiant-energy coefficient
Blackbody	1.0
Lampblack	0.95
Asbestos board	0.93
Steel, oxidized	0.79
Copper, oxidized	0.72
Lead, oxidized	0.63
Cast iron	
Oxidized	0.62
Bright	0.22
Brass	
Oxidized	0.60
Polished	0.10
Nickel, oxidized	0.42
Zinc, oxidized	0.11
Silver, polished	0.03
Aluminum	
Polished	0.04
Oxidized	0.11
Paper	0.93
Aluminum paint	0.30
White enamel	0.64
Black lacquer	0.87

where h_b = watts per square inch, t = temperature gradient. These equations apply to vertical planes more than 12 in high. For heights less than 12 in, multiply the coefficient in Eq. (21-7) or (21-8) by the constant noted below.

Height, in	Constant
8	1.35
6	1.53
4	1.76
2	2.70

The rate of heat transfer by natural convection from a horizontal surface facing upward is about 35% greater and a rate from a horizontal surface facing downward is about 30% less than from a vertical surface. Hence, for average conditions, and on the sides of the body exposed, the average rate of heat transfer by natural convection is well represented by Eqs. (21-7) and (21-8).

If the natural-convection heat transfer is to a surface, the portion affected is the reverse of that stated for transfer from a surface. This does not affect the average rate of heat transfer.

Forced Convection. The velocity of the gas is a dominant factor in the transfer of heat by forced convection. The flexibility of its control, together with the penetrating property of gases, makes forced convection an effective method of heat transfer in many cases. Forced convection can also be applied to fluids.

In electric-heating practice the main limitation on the use of forced convection on gases is the upper limit of operating temperature of fans, about 650°C (1202°F). In some cases the gas can be heated after leaving the fan, and thereby higher temperatures than that noted above can be used.

There is in each use of forced convection a requirement of defined passages for the movement of the gas. This method also entails an investment charge for the fans, ducts, etc., and requires an expenditure of additional energy.

Some of the more common arrangements of surfaces with various conditions of forced convection have been studied, and relate to (a) gases flowing in pipes and (b) gases flowing past plane surfaces.

Finned Surface. If the heat-transfer coefficient of a surface is less than the heat-transfer coefficient which is the measure of the rate of flow of heat through the body, to or from the surface, the addition of fins or ribs to the surface will increase the rate of heat flow to or from the surface.

As a general rule, a spacing and dimensioning of fins that increase the surface area seven to nine times is good practice. The height of the fins should not exceed 3 to 4 times the spacing.

The principle of increasing the surface area per unit length of the surface by the addition of fins is equally applicable to the transfer of heat by radiation.

Heat Absorption. The rate of heat absorption for given external thermal conditions is determined by the diffusivity coefficient of the substance. This coefficient is defined as the ratio of the thermal conductivity to its heat-storage capacity per unit volume; thus

$$n = \frac{k}{p_c} \quad (21-9)$$

where k = thermal conductivity, p = density, and c = specific heat. This coefficient is but little affected by temperature.

The heat absorbed by a material for a given temperature rise is

$$q = \frac{w \times c_m \times t'}{3,412} + L + R \quad \text{Wh} \quad (21-10)$$

where w = weight in pounds; t' = temperature rise in degrees Fahrenheit; c_m = mean specific heat over the temperature range; L = latent heat, if any, in watthours; and R = heat of reaction, if any, in watthours.

Heat of reaction here means the quantity of heat that must be added to the charge or subtracted from the charge, depending on whether the reaction is endothermic or exothermic.

The total heat required in a given case is the sum of the heat absorbed by the material, that is, the charge and the heat loss of the operation. The corresponding average power input is the total heat in watthours divided by the time of the heat cycle in hours. The power-time characteristic is individual for each class of heating surface.

Thermal Efficiencies. The conversion efficiency of the heating device is the ratio of the heat absorbed by the material, that is, the charge for a given temperature rise and the corresponding heat input to the device. If the charge is under cover, the heat absorbed by the material of the enclosure (the heating chamber) must be taken into account, along with the heat dissipated from the outer surface of the chamber. With increase in length of heat cycle the heat stored in the materials of the enclosure affects the conversion efficiency less and less, and with continuous operation it is usually negligible.

The operating efficiency expresses the combination of the conversion efficiency and the efficiency of the method of operation. If containers or removable supports for the charge are used, it is necessary to distinguish between net and gross operating efficiencies; the latter includes the heat absorbed by the containers or supports. A much-used rule of thumb for preliminary estimates is an operating efficiency of 50% for many heat applications under cover.

Thermal efficiencies are expressed as watthours per pound, pounds per kilowatthour, kilowatt hours per ton, etc., according to the scale of the operation.

High-Density Electromagnetic Force. Usually utilized to achieve fast heating times in air, vacuum, or gas atmospheres, this method of heating is more commonly known as induction heating. The electromagnetic force is developed at some frequency through the utilization of a suitable conducting coil. The coil is generally made of copper, often it is liquid-cooled, and it is designed to encircle or to be in close proximity to the material (nominally metal) to be heated. The high-density electromagnetic force coupled to the metal load induces current to flow in the load, and this current directly heats the material.

Concentrated Electrostatic Fields. Usually applied to fast heating times in air, vacuum, or gas atmospheres, this method of heating is more commonly known as dielectric heating. The electrostatic field is developed at a very high frequency. Through the utilization of metallic plates (often copper) placed above and below or on either side of the material to be heated (nominally a nonconductor) the electrostatic field causes a rapid reorientation of the molecules in the load, and heat is thereby produced internally.

Industrial Heating. This is classified as follows:

1. The heating of materials to temperatures below the temperature at which a change of state occurs
2. The heating of materials to cause a change of state, that is, evaporation and melting
3. The heating of materials to bring about a chemical reaction

21.12.2 Methods of Electric Heating

The methods of electric heating are

1. Resistance heating = I^2R effect
2. Electric arc
3. Induction heating = special application of I^2R
4. Dielectric heating

The resistance method and the induction method are widely employed. The use of the electric arc is generally confined to high-temperature applications. Dielectric equipment is widely used for the heating and welding of nonconductors.

Alternating current is used in most applications of electric heating. Direct current is required for a thermal process in which electrolysis is involved.

Resistance heating combines the basic attributes of electric heat with the ability to provide efficient temperature control up to 5425°F (3000°C). Apart from mechanical automation for material-handling systems, the trend to automate overall processing will continue.

I^2R effect is expressed by the equation

$$q = i^2 r t = \frac{e^2}{r} t \quad \text{Wh} \quad (21-11)$$

where r = resistance of the path of the current in the load; i = the current in amperes, for varying current, the rms value; e = applied voltage, across load; and t = time, in hours, of the flow in current.

The resistivity-temperature coefficient of metals is positive; that of nonmetals, negative. An exception among nonmetals is graphite.

The relation between applied voltage and change of resistance—a general case in heat applications—for constant power is

$$e_2 = e_1 \frac{z_2}{z_1} \sqrt{\frac{r_1}{r_2}} \quad (21-12)$$

or if the power factor of the circuit is unity:

$$e_2 = e_1 \sqrt{\frac{r_2}{r_1}} \quad (21-13)$$

where e_1 = initial voltage, r_1 = initial resistance, z_1 = initial impedance, r_2 = new resistance, z_2 = new impedance, and e_2 = new voltage.

The rate of heat development, that is, watts, is obtained by dividing the quantity obtained by Eq. (21-11) by the time period in hours or frequencies of an hour.

In indirect resistance heating, the heat is developed in resistors (heating units), a circuit apart from the charge, and is transferred from the surface of the resistors to the surface of the charge by one or more of the modes of heat transfer, namely, conduction, radiation, and convection (natural or forced).

If the heat transfer is by conduction, the resistor must be in contact with the charge. An enclosure for the charge (heating chamber) is required for heat transfer by radiation and convection.

21.12.3 Electric Heating Equipment

Resistors. The materials in general use for resistors for medium- and low-temperature surfaces are the two alloys B82 and B83 designated by the ASTM.

B82 Alloy. Additional data on round wires and rectangular sections are given in Table 21-7. Approximate maximum operating temperature is 1160°C (2100°F).

B83 Alloy. See the footnotes to Table 21-7. Approximate maximum operating temperature is 900°C (1652°F).

The melting ranges of these alloys are narrow. They do not soften if the temperature of the resistor is kept at a reasonable margin below the melting range. The coefficients of expansion are low, and the change of resistance with the change of temperature is small. The resistivities permit the use of reasonable cross sections and lengths at standard low-distribution voltages.

These alloys have the prime requisite of resistance to oxidation and scaling when operated in the air. However, this protection is not perfect, and it decreases in value with increases of resistor temperature. The alloys are susceptible to harm from compounds of sulfur and are affected to some extent by carbon monoxide. Unexpected causes of chemical action on resistors of these alloys are foreign gases or gases evolved from the material being heated.

TABLE 21-7 B82 Alloy (Ni-Cr) Average Values

No. B & S	Diameter, in	Surface area, in ² /lin ft	Ω/ft straight round wire, at 20°C*	Ft/lb bare round wire [†]
1	0.289	10.91	0.00778	4.18
3	0.229	8.65	0.0124	6.66
5	0.182	6.86	0.0196	10.5
7	0.144	5.44	0.0314	16.8
9	0.114	4.31	0.0500	26.9
11	0.091	3.42	0.0785	42.2
13	0.072	2.71	0.1250	67.4
15	0.057	2.15	0.200	107
17	0.045	1.71	0.321	172
19	0.036	1.35	0.502	26
21	0.0285	1.073	0.800	430
23	0.0226	0.851	1.27	684
25	0.0179	0.675	2.03	1,090
27	0.0142	0.535	3.22	1,730
29	0.0113	0.424	5.09	2,730
31	0.0089	0.337	8.21	4,420
33	0.0071	0.267	12.90	6,930
35	0.0056	0.212	20.70	11,150
37	0.0045	0.168	32.10	17,200
39	0.0035	0.133	53.10	28,400

*For B83 alloy, multiply by 1.037.

†For B83 alloy, multiply by 1.02.

In addition to the B83 alloy, several other similar alloys are listed by manufacturers for low-temperature service.

It is often desirable for low-temperature heating applications to use resistors known as metal-sheath heaters. These devices provide a metal sheath, usually a nickel alloy or a stainless steel, as a protective cover over the resistance device and insulated from it by a magnesia oxide. Sheath heaters are ideal for direct immersion and conductive heating, as the sheath tends to assume the temperature of the resistance element. Direct contamination of the resistance element is thus avoided.

Resistors for operating temperatures above 1150°C (2100°F) are made of silicon carbide, molybdenum, tungsten, and graphite.

Silicon carbide is the basis of a resistor material for operating in air for temperatures up to about 1500°C (2732°F). The material is formed into rods of diameters and lengths for combination into circuits of required electrical rating. The range between the cold and hot resistances is small enough to permit single-voltage operation. The resistance gradually increases with use, and an autotransformer with taps to compensate for this increase of resistance is desirable.

Molybdenum resistors are suitable for temperature up to 1650°C (3002°F). This metal is ductile enough at room temperature for drawing into wire for resistor windings. The wide range between the cold and hot resistances makes multiple-voltage operation necessary. The supports (insulators) of the windings should be of magnesia or zirconia. Molybdenum resistors cannot be operated in air and also must be protected against reactions with silicon and carbon. The metal is immune from reactions with sulfur, nitrogen, hydrogen, and water vapor. A hydrogen atmosphere is ordinarily used for the protection of these resistors. Molybdenum is not suitable for resistors of vacuum furnaces because of its high vapor pressure.

Tungsten resistors can be used for temperatures up to 2000°C (3632°F). The maximum temperature is limited by the refractory supports of the resistor. The metal must be heated for drawing into

shapes. The resistivity-temperature characteristic is practically the same as that of molybdenum. The low vapor pressure of tungsten makes it useful for resistors of vacuum furnaces.

Graphite resistors are suitable for any temperature that can be used. The resistors must be protected against oxidation above about 600°C (1112°F). Also because of the chemical activity of carbon, special consideration must be given to the atmospheres surrounding the resistors. The material is available in a wide range of shapes and dimensions.

The *useful life* of a resistor (barring accidents) is dependent mainly on the temperature at which it is operated. That temperature must be high because of the required rate of heat transfer per unit area of the surface. Thus the operating temperature of a resistor is a function of the surface power density (watts per unit area) of the resistor. For a resistor of given shape and dimensions the operating temperature will vary with the watts input, since the surface area remains the same. Hence, watts per unit area is a first consideration in resistor design. This value in practice varies according to the conditions of use.

A rectangular shape for the resistor section gives a greater surface area for a given resistance than the round shape (Figs. 21-11 and 21-12); hence, the frequent use of the ribbon, or strip, form of resistor, particularly for the upper range of temperature. The cast resistor for furnaces also embodies this principle.

The *maximum voltage* of resistor circuits is limited by electrical insulation and elevated temperatures and by safety considerations to 600 V. This value may be exceeded in special cases. Standard distribution voltages and standard frequencies are used. Resistor windings may be in one, two, or more circuits and may be connected either single-phase or polyphase.

As a general rule, the *heat-equalizing effect* of the heat-storage capacity of the charge into the surrounding enclosure (if any) makes permissible voltage fluctuations within reasonable limits. However, the average voltage must be equal to the normal voltage to maintain the normal heating rate. The relation between heating rate and voltage is shown in Fig. 21-13.

The *power input* to resistors supplied from constant-voltage circuits can be varied by the use of multiple circuits and series-multiple-switching combinations. Another method is the use of an autotransformer or transformer with taps. With 3-phase resistor circuits the change from delta connection to wye connection, and vice versa, is available. In each case the power input to the resistor is proportional to the square of the voltage. For example, with the change from delta to wye the power input is reduced to one-third its value with the delta connection.

Other devices are available for power controls such as saturable reactors, regulated or unregulated; variable inductances; and stepless variable autotransformers.

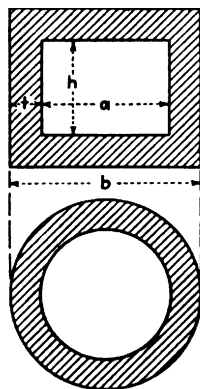


FIGURE 21-12 Shape factor—cylindrical enclosures.

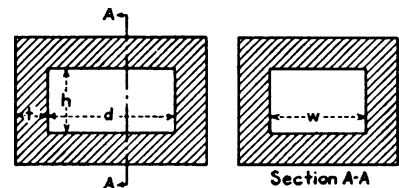


FIGURE 21-11 Shape factor—rectangular enclosures.

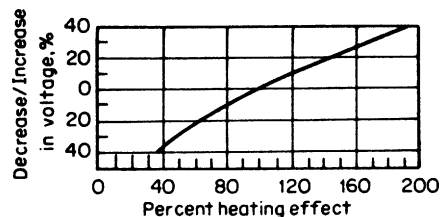


FIGURE 21-13 Variation of heating effect with changes in voltage.

Self-Contained Units, Water Heating, and Steam Generators

Resistor heating equipment includes many small devices such as electrically heated tools, appliances of various kinds, self-contained units, ranges, water heaters, stills, sterilizers, and baths. The larger units include ovens, kilns, lehrs, furnaces, etc. Each of these descriptive terms relates to a field—some more general than others—of electric heating service.

Small devices are often used. As a rule the best design of a resistor for any small device is obtainable only by trial. The space is generally limited, and the conditions which affect heat transfer vary widely. For many devices a useful guide is 20 W/in² of resistor surface. Both higher and lower values are used according to the conditions in each case. Metal-sheath heaters can be obtained for operation at many wattages to be operated at specified voltages of 115 or 230 V.

Self-contained units meet manifold needs for localized heat in small quantities within the lower temperature range and extending up to about 815°C (1500°F).

The construction of these units consists of a resistor of the 80 Ni–20 Cr alloy embedded in a heat-resisting material such as powdered fused magnesia and enclosed in a cylindrical metal sheath. In many cases they are applied for direct-contact heating, that is, for heat transfer by conduction.

The forms of the self-contained heating units include insertion (or cartridge) units, straight or curved tubular units in a shape to conform to the method of use, space (or strip) heaters, immersion units for heating liquids, fin-type units for air heating, cast-in units, and a special construction for melting soft metals.

Standard voltages of self-contained units are 115, 230, and 460 V. Space restrictions of the terminals do not permit higher voltages except for special designs. The ratings of these units range from 30 W to 10 kW.

Space Heaters. These are made in two types:

1. With steel sheath; specific rating 10 W/in² of surface; maximum operation temperature 399°C (750°F)
2. With porcelain-enameled steel or alloy-steel sheath; specific rating 15 W/in² surface; maximum temperature 650°C (1200°F)

Both types are used for ovens, warming tables, process machinery, space heating, etc.

The rating in watts per square inch of affected area of the sheath of the unit is considered in relation to its application: (1) the resistance to oxidation or other chemical action and (2) the rate of heat absorption by the surrounding medium. Immersion units for heating water have comparative ratings, 40 to 50 W/in². However, these units should always be installed so as to permit free circulation of water, and they should not be operated unless completely submerged.

Oils in general do not absorb heat as rapidly as water. Also, immersion units in oil accumulate carbon deposits on the sheath. Hence, units for this service have a much lower rating—20 to 25 W/in². Steel is a satisfactory sheath material for mineral oils. Other oils must be given individual consideration with reference to the chemical action on the sheath material. The same consideration applies to heating chemical materials in liquid form; for example, a unit with a lead sheath is used for nickel and copper solutions.

The temperature-watts characteristic of the fin-type units is given in Fig. 21-14.

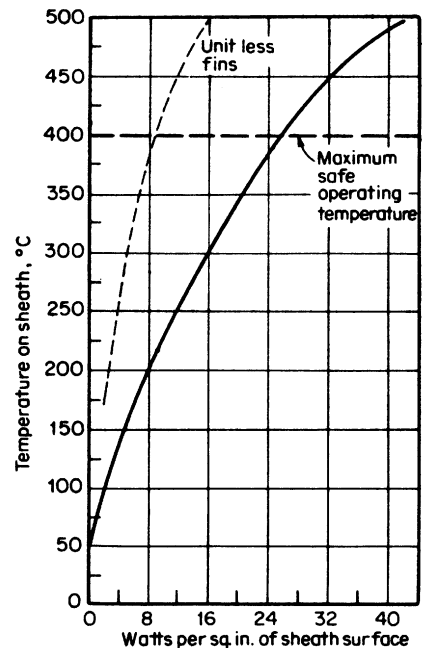


FIGURE 21-14 Temperature-watts characteristics of fin-type unit in still air.

Room Heating. The space heater is well adapted to heating rooms; radiation and natural convection are used for the heat transfer.

An approximate equation for the rate of heat loss from structures or ordinary building construction is

$$kW = \frac{(0.02NV) + (1.13G) + kA}{3412} (T_r - T_0) \quad (21-14)$$

where N = number of air changes per hour (usually two or three)

V = room volume, ft^3

G = area of windows, ft^2

A = area of ceiling and exposed walls, ft^2

$T_r - T_0$ = temperature difference, $^{\circ}\text{F}$, between inside and outside

k = heat-transfer coefficient, $\text{Btu/h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F}$

Average Values of k

Wood construction	0.25
8-in brick wall	0.50
12-in brick wall	0.36
6-in concrete wall	0.79
10-in concrete wall	0.62

The heat-transfer coefficient can be reduced by the addition of proper insulating material in the walls and ceiling of the room. Other heat sources must be considered in determining the actual heating-equipment requirements, such as lighting, appliances, machinery, and people.

A heating cable with a lead sheath for temperatures up to 74°C (165°F) has a variety of uses, for example, warming soil to promote plant growth, prevention of freezing of liquids in pipes, and keeping gutters and downspouts open.

Electric Steam Generators. These are made in three types:

1. With immersion heating units up to 300 kW, single-phase, standard low voltages
2. With 80 Ni-20 Co alloy resistors mounted in the tubes of a fire-tube boiler; sizes up to 1000 kW, single-phase or 3-phase, standard low voltages
3. Electrode type: large units 200 kW and above; all 3-phase, either 2300 or 6600 V

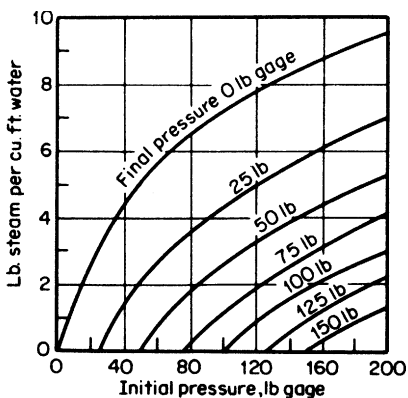


FIGURE 21-15 Flashing capacity of steam generators.

The heat loss from a generator in operation is the sum of the loss through the heat insulation and the loss by conduction through the pipe connections. The time of heating is very short and the total loss within a given time is small compared with the heat output in the steam. Hence, the insulation of the shell can be moderate in amount for a high conversion efficiency—95% to 97% and higher. This efficiency is usually given as 3 lb of steam/kWh. The boiler-horsepower rating is one-tenth the kilowatt rating.

There is little storage capacity in a steam generator, and the power demand cannot be reduced by storage as in water heaters. When a quantity of steam beyond the rating of the generators is required, it cannot be obtained by releasing the steam through a pressure-reducing valve. The amount of steam thus available per cubic foot of water in a generator can be read from Fig. 21-15.

The auxiliary equipment of electric steam generators is the same as that of fuel-fired steam generators. However, full automatic control is more frequently used with the electric steam generator. The main use of the small sizes of electric steam generators is for the supply of steam at points which cannot conveniently be reached by steam pipelines and in locations where the fuel-fired unit is not permissible.

The larger units have been applied mainly for utilization of the excess water capacity of hydro-electric plants and by industrial plants which require large quantities of processed steam, for example, paper mills.

Resistor Ovens

The two types of resistor ovens are convection and radiation.

An *oven* is a low-temperature heating chamber with provision for ventilation.

Oven service is drying and baking. Drying is the removal of liquids by evaporation. The rate of drying is limited by the rate at which the liquid will move from the interior of the mass. This is a limitation on the power input. The effect of a too high power value is skin drying.

Baking is a hardening process which involves chemical and physical changes in the material. If a material contains a solvent, much of that component is removed during the first stage of baking. Air drying preliminary to baking may be advantageous.

The technique of baking is a correlation of temperature and time. The general rule is: The higher the temperature, the shorter must be the heat cycle. The temperature-time relation for each material is individual and must be determined by trial.

Ventilation. As a rule, the ventilation of oven chambers is forced by means of fans. The removal of inflammable vapors is a special procedure.

Convection, Box, and Continuous (Air) Ovens

Convection Ovens. The transfer of heat is by forced convection in gases, mainly air. Steel panels are used for the enclosure of the heating chamber. A double wall with inner heat insulation is general practice. The heat-storage capacity of these enclosures is small.

Box Ovens. Box ovens—batch or stationary heating—are of two designs:

1. Heating chambers with hooks, racks, or shelves for the support of the charge
2. Heating chambers arranged to receive drawers, trucks, or similar removable supports for the charge

Continuous (Air) Ovens. These ovens are flexible in design. The structure may be horizontal, with or without inclined entrance and exit, or vertical. The travel of the charge may be one-way or a U-shape movement. The latter permits the absorption of heat from the outgoing material by the incoming material. The chain conveyor is applicable generally.

Radiation Ovens

In radiation ovens, heat is transferred by radiation. The heating units are tungsten-filament lamps (heating lamps) with self-contained or external reflectors.

Standard heat lamps are 125, 250, 375, 500, and 1000 W, 115 V. The self-contained reflector lamps of the first three ratings are most generally used. The filament temperature around 2500 is low enough to give a comparatively long life, average 5000 h or more. The large part of the radiation from filament lamps is in the infrared region of wavelengths; hence the term *infrared heating*.

Construction of the radiation oven is similar to that of the convection oven. The main difference is the detail incident to the lamp-type heating units. The general arrangement is a bank of heat lamps which surrounds or partially surrounds the charge. In a continuous oven this bank forms a tunnel through which the charge travels. This type of oven is frequently built with metal-sheath heaters as

a source of infrared energy. High temperatures are available through the use of quartz-infrared units, used particularly in higher wattage ratings.

General service is drying and baking processes which require temperatures below 315°C (600°F). The method is best adapted to continuous horizontal ovens for heating charges, which present a large surface area in proportion to the mass, for example, sheet metal, textiles, paper, and some plastics, and require only surface heating.

Absorption coefficients of the surface of charges should be reasonably high. Correspondingly, the inner wall surface of the heating chamber should have a low absorption coefficient. Aluminum linings are used in many cases.

Concentration of radiation (power density) on the charge surface depends on the wattage and spacing of the lamps; the efficiency of the lamp reflector units; and, to a limited extent (within the range of practice), the distance between the lamps and the surface of the charge.

21.13 ELECTROMAGNETIC INDUCTION

Classification. Electromagnetic induction is a process used to heat metals for purposes of hot working, heat treatment, welding, and melting.

In the hot-working area, induction is used largely for through preheating prior to forging and extrusion; it has been found to be economically attractive as an alternative to conventional gas-furnace heating processes. The application of induction for slab preheating, although in commercial use, has not attained as high a level of acceptance.

The prime application of induction in the heat-treating field is in the area of surface hardening. It is widely accepted as the principal means of surface hardening for a wide variety of mass-produced parts. In some applications, competition appears to be coming from ion nitriding, laser hardening, electron-beam hardening, and high-frequency resistance hardening. By and large, the first three of these processes do not appear to offer a threat to the induction market. The development of high-intensity induction surface hardening and high-frequency resistance heating and hardening (which employs similar radio-frequency equipment) can be employed to produce the very shallow case-hardened depths achievable by the other three processes.

The use of induction for through heat treatment is less widespread than for surface hardening. This is particularly true for some processes as tempering and annealing. Recent research work has suggested that such applications may indeed be feasible with induction, however.

High-frequency induction and resistance welding are considered to be well-established processes. High production rates and low cost are two of the main factors which make it more attractive than competitive processes such as arc welding in high-volume areas such as pipe and tube production.

Although induction heating is a well-established technology, development efforts in such areas as higher-efficiency equipment, coil design, and automation should enable the process to retain and possibly to enlarge its markets.

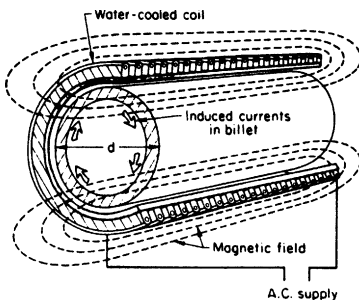


FIGURE 21-16 Basic principle of induction heating illustrated for a tubular conductor heated by a solenoid coil.

Principle of Operation. The material to be heated is exposed to an alternating (or varying) magnetic flux. The material to be heated must be a conductor so that currents are thus induced in the material (or load) and flow wholly within its mass. Generally this type of heating is produced by an electromagnetic field caused by an alternating-current source. It is possible, however, to produce similar results, but at lower current densities, with a high-flux permanent magnet moved at high speed across conductive materials. The term *eddy-current heating* is sometimes applied to the method.

Assemblies. One of the simplest induction-heating setups is shown schematically in Fig. 21-16. Here, the induction

coil, or simply inductor, is a helical (or solenoidal) copper conductor carrying an alternating current which surrounds a tubular workpiece. Associated with the ac is a magnetic field whose flux lines pass through the workpiece. The strength of the magnetic field varies with the ac; in so doing, eddy currents are induced in the workpiece. Generally, the induced current path is parallel to that of the currents in the inductor.

For a given workpiece and coil arrangement, the heating rate can be adjusted by increasing or decreasing the induced current in the workpiece. This is done by adjusting the coil current which is controlled by the ac or induction generator. If the workpiece is magnetic (for example, steels at low temperature), additional heat is produced by hysteresis losses. Such heating is usually small but, in some cases involving strong magnetic fields, it can become significant.

Shape of Load. The ideal load shape is a cylinder. It may be a solid, or a tube. Shape alone does not affect the principle involved. It may introduce some complications in geometry. Any shape load can be heated by the inductive method, but not always to obtain the desired results. Special techniques are required for some unusual shapes.

Basic Relations. For a cylindrical load and other loads where the coil encompasses the load, the directions of the magnetic flux are parallel to the longitudinal axis of the load and hence to its lateral surface. The factors which, for a given intensity of longitudinal magnetic flux at the lateral surface of the load, determine the rate of heat development in the load are

1. The electric and magnetic properties of the material
2. The frequency
3. The radius, or one-half the thickness of the charge

Heat Concentration. In considering a solid load, it is necessary to visualize the current subject to skin effect induced to flow in circular paths parallel to the circumference of the load. Each circuit possesses inductance, and there is a subsequent progressive decrease in current strength radially. The rate of decrease changes with frequency.

The Rate of Heat Development. The general equation for the rate of heat development by symmetrical currents in a long load (length much greater than its diameter) of any shape for a longitudinal and sinusoidal alternating magnetic flux at its lateral surface is

$$P = H^2 SL \times \sqrt{\mu f} \times \sqrt{p_a \times 10^9} \times 10^{-7} \quad \text{W} \quad (21-18)$$

$$H = \frac{4\pi N \times \sqrt{2i}}{10L} \quad \text{Oe} \quad (21-19)$$

where p_a = resistivity of the material of the load in ohm-centimeters cubed
 μ = permeability of material of the load
 S = shape factor of the load
 L = length of the load in centimeters
 N = number of turns in the coil around the load
 i = current in the coil, A

Magnetic Charges. The ac excitation curve of the magnetic material more or less coincides with the dc magnetization curve as saturation is approached. Hence, the latter curve (usually more readily available) can be used as a reference in induction heating. For values of H higher than that required for saturation, the value of μ corresponds to the saturation values of p of H .

Permeability. Permeability is dependent on frequency up to around 10 kHz. Above that frequency, permeability decreases to some extent with increase of frequency, but this effect is not well defined.

Hysteresis. In induction-heating practice, the rate of heat development by hysteresis in a magnetic material at room temperature is a small percentage of the eddy-current watts. The hysteresis watts decrease rapidly with rise of temperature. Hence, hysteresis is a negligible factor in the inductive method of heating.

Primary Coils. Single-layer coils are standard practice. Tubular conductors—round, oval, or rectangular—provide for water cooling of the coil.

The number of turns is selected with reference to the desired relation of amperes and volts for a given service. The restrictions on this choice are the space required for conductor insulation and the requirement of water cooling.

21.14 ELECTRIC WELDING

21.14.1 Resistance Welding

Resistance welding includes spot welding, projection welding, seam welding, and butt welding. All are based alike on the principle of resistance heating but differ in the details of application.

Spot welding is applied to overlapping sheets. These are clamped between water-cooled electrodes, pressure is applied, and a current impulse is passed through the assembly. The material in the zone of pressure is heated to fusion, and the joint thus made to cool under pressure.

Spot welding is largely employed on sheets 0.025 to 0.125 in thick, although welds on thicker sheets and plates up to 1 in thick are made regularly.

The area of the spot weld is small; weld diameters of 0.25 to 0.625 in are the usual range. The maximum diameter is limited by the area of uniform contact between sheets that can be obtained with practical pressure.

Rapid heating by using high current values is necessary to bring the metal that is to form the joint to the required temperature without more than normal heating of the adjacent metal. Current values range from 5000 A upward. The voltage between the electrodes is usually less than 2 V. The open-circuit voltage is generally less than 12 V. The time period of current flow varies widely, depending on the thickness of the sheets, kinds of material, etc. For thin steel sheets this period is about 1 c ($1/60$ s) for each 0.010 in of the total thickness of the two sheets to be joined. The pressure, current value, and time are variables that must be correlated in each case.

Spot welding with a single current impulse is limited to sheets not thicker than about 0.125 in. Because of the heating of the electrodes, and consequent short life, with heavier material, thick sheets are welded by using a number of current impulses, for example, 4 c on, 2 c off, repeated as required. The no-current intervals, that is, cycles off, prevent the overheating of the electrodes.

Projection welding differs from spot welding only in the use of the buttonlike projection on one of the sheets to define the path of the current. A number of adjacent welds can be made simultaneously without interference, a useful method for assembly work.

Seam welding can be made by putting a series of spot welds on thin sheets by passing the sheets between two pressure electrodes (Fig. 21-17) and with continuously interrupted current. Speeds range from 10 to 400 in/min; approximately 60 in/min is the most common speed. Twelve welds per inch with 6- to 10-in-diameter electrodes is representative practice.

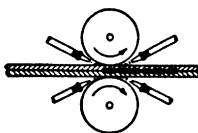


FIGURE 21-17 Seam-welding electrodes with water cooling.

Sometimes classed as seam welding but otherwise known as edge welding is the type of welding accomplished on continuous tube mills, or continuous butt-welding installations where the edges of metal are brought together and welded as a seam. In this type of welding pulsed currents are not used to obtain the weld, but rather a continuous ac or dc supply fed through rotating electrodes to the abutting edges of the seam produces the electric energy required for the weld.

The *variables* in these three methods of welding which must be correlated are

1. Electrode diameter, material of electrodes, contact area, cooling, and pressure
2. Nature and surface of metal or metals to be welded
3. Timing of current flow
4. Current value and waveform

Timing circuits for resistance welding are either (1) nonsynchronous or (2) synchronous (relating to the welding current zero).

Nonsynchronous timers are of various types, ranging from the simple application of foot pressure to close and open the welding circuit, according to the judgment and skill of the operator, to the combinations of cams, limit switches, etc., the functions of which are independent of the operator.

The synchronous timers are electronic, using thyatrons and ignitions. The most simple of these are those which are adjustable, as regards to current impulse, in 1-Hz steps. When used with an ac supply, the ignitron contractor will pass current each half cycle that the anode is positive. A second ignitron is connected inversely to pass current during each of the other half cycles.

Electronic control for resistance-welding circuits is inherently a precision device. The choice between the two types of control is primarily a matter of the value of exactness in timing, which becomes more important as the welding time is decreased.

Current control in welding circuits, that is, the control of the rate of heat development, is obtained by taps in the primary winding of the welding transformer or by phase control of the welding current, retarding the point at which current starts to flow in each half cycle beyond the power-factor angle. A combination of the two methods is often used.

Percussion welding is a self-timing spot-welding method. A current impulse is obtained by the discharge from a capacitor or from a magnetic field. (This method is usually classified under dc resistance welding.) The capacitor arrangement for percussion welding is used extensively in the manufacture of lamp filaments.

Butt-Welding Upset Method. End-to-end welds, lap welds, and butt welds are included here. The faces of the parts should be prepared for even contact. The parts are clamped and brought together by hydraulic pressure, thus closing the circuit. Plasticity occurs simultaneously over the entire contact area. The joint is cooled under pressure. The method has a wide variety of applications, large and small. In continuous pipe welding, the current is conducted to the work by a pair of rotating electrodes. This, as previously mentioned, is sometimes referred to as the seam-welding technique. Butt welding can be obtained by utilizing induction-heating equipment; how this can be accomplished will be described later.

Flash Welding. No preparation on the face is necessary. One face is stationary, the other movable. Voltage is applied through pressure contacts. A momentary contact establishes current flow and flashing (the melting and vaporization of the minute contact points). The movable face is fed forward continuously at the rate at which the metal is melted. The pressure of the gases developed between faces prevents the access of air to the hot faces and blows out the molten metal. The metal adjacent to the faces becomes plastic, and the joint is made by fusing the parts together by hydraulic pressure. The circuit is opened by a jam relay as the faces make contact. However, if a considerable amount of flashing is required to remove impurities, the circuit is held closed for a predetermined time and may be opened just prior to the application of the last pressure value.

21.14.2 Arc Welding

Welded joint is a union of metal parts made by localized heating, without pressure in arc welding and supplemented by pressure in resistance welding. The technique of welding is built around the methods of concentration of heat and is based on the metallurgy of welds in the mechanics of joints.

Arc-Welding Manual Operation. Methods of arc welding are classified as follows:

1. Direct-current arcs, one electrode—metal or carbon
 - a. Unshielded arc
 - b. Shielded arc
2. Alternating-current arcs, metal electrodes
 - a. Unshielded arc, one electrode
 - b. Shielded arc, one electrode
 - c. Shielded arc, two electrodes (atomic-hydrogen process)

Joints. The five principal types of arc-welded joints are butt joints, corner joints, edge joints, lapped joints, and T joints. Any length of joint can be made by travel of the electrode; one or more passes may be required.

The position of the joint (see Fig. 21-18), especially for multipass work, is an important factor in the economics of welding. The maximum welding speeds obtained with the flat position are about twice as fast as those with the horizontal position and about 4 times faster than the maximum speeds obtained with the overhead and vertical positions. Welding in the flat and horizontal positions is much easier for the operator than overhead welding—so much so that the arc can be kept in operation about twice as long per hour of overall time. Likewise, vertical welding is less tiresome than overhead welding and represents an increase of about 50% in welding time without an increase in the fatigue of the operator.

The *weldability* of metals and alloys can be stated as easy, intermediate, and difficult to weld. This term, when used with reference to carbon steel, relates to carbon content. Carbon steels up to about 0.30% C are easy to weld. That class of steels is used in a large part of the fabrication of materials by welding. Practically all metals and alloys can be electrically welded, but in many cases an individual study of the metal or alloy, dimensions, and position of the weld is required to develop the particular technique necessary.

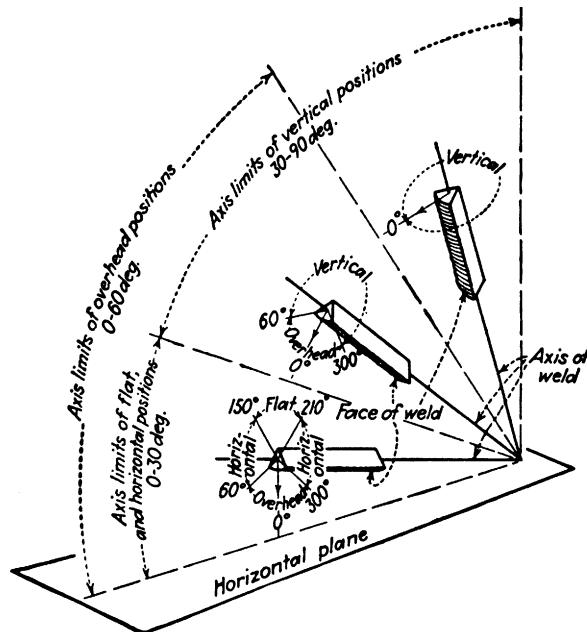


FIGURE 21-18 Position of welds in arc welding.

A characteristic feature of arc welding is that symmetrical sections (I beams and T beams) can be used.

Single-Electrode Welding. The arc is maintained between the electrode and the work. Round steel electrodes, with carbon content suited to the class of work, supply the metal (filler metal) for the joint.

The phenomenon of the transport of the molten metal from the electrode to the work is dependent on the position of the joint. It is, however, a factor in the selection of the electrode for each joint position. The making of a sound weld requires that the filler metal be deposited only on molten-base metal. The depth of the molten-base metal is termed *penetration*.

Metal Electrode Types. There are two basic types:

1. Bare electrodes (or lightly coated electrodes)
2. Coated electrodes

The bare electrode is covered with a film or its oxide to aid in stabilizing the arc circuit. This type of electrode is used mainly for joints which carry only static loads; the coated electrode has a jacket made of either organic (combustible) or inorganic material or a combination of the two types. This coating serves several purposes:

1. The organic material provides the gaseous shield to restrict the access of oxygen and nitrogen (air) to the molten metal.
2. The inorganic material makes a slag to refine the molten metal. (The principle is the same as the refining of steel and the manufacture of steel in an arc furnace.) This slag also serves as an insulating blanket to retard the rate of cooling of the weld metal.
3. The gas envelope and the slag aid materially in the stabilization of the arc circuit.
4. In some cases the coating is used to add alloying elements to the weld metal.

Electrode coatings are of different types, corresponding to the class of weld service (kind of base metal, joint position, etc.). The selection of electrode size, carbon content, and type of coating is a major consideration in welding practice.

Powdered-Metal Electrodes. Some electrodes are available which have powdered iron, which will make up a good portion of the metal to be deposited in the joint, mixed in with the flux coating. This makes the electrodes much larger on the inside for the same-diameter core wire as standard flux-coated electrodes. These electrodes are well suited to down-hand welding and are said to deposit more metal in a given period of time than standard flux-covered electrodes.

Low-Hydrogen-Type Electrodes. Some types of steel welding rods have special treatment during manufacture to reduce the amount of hydrogen in the coating. The reduction of hydrogen in the coating produces a weld with little or no absorbed hydrogen in the base metal and reduces the likelihood of underbead cracking.

Electrode Quantities. The weight of electrode metal required for a given joint is

$$W = \frac{\text{weight of metal deposited}}{l - \text{electrode loss}} \quad (21-20)$$

The weight of metal deposited is calculated from the volume required to fill the joint plus reinforcement, if any. The electrode loss is the sum of the scrap end loss, the spatter loss, and the coating loss. The scrap end loss varies with the diameter and length of the electrode. With 14-in electrodes the loss varies from 10% to 20%. The average value of this loss is about 17%.

The other losses depend on the type and size of the electrode, joint position, welding current, arc voltage, and skill of the operator. With bare electrodes these losses vary from 8% to 15%, average 13%; with coated electrodes, from 15% to 35%, average 27%.

Carbon (Graphitic Carbon) Electrodes. These are used with direct current for arc welding of non-ferrous metals and alloys and with the addition of external shielding (gases from material placed adjacent to the arc) for welding steel. The weld metal is supplied by melting a portion of the base metal. If additional metal is required, it is supplied by a filler rod. Carbon electrodes are not suitable for vertical and overhead welding. The use of a carbon electrode is declining.

The DC Arc. The dc arc is adapted to practically any class of welding service. The arc voltage varies with the type of electrode, ranging from 15 to 40 V. Both straight polarity (work positive, electrode negative) and reverse polarity (work negative, electrode positive) are used, depending on the character of the work. (Polarity here relates to the difference in the rates of heat development at the anode and cathode of the dc arc.) Metal electrodes should be selected with reference to the polarity arrangement. Carbon electrodes can be used with either arrangement; straight polarity is more common practice.

The rotating dc-generator single-operator unit, with a drooping voltampere characteristic, driven by any type of prime mover, is made in sizes ranging from 159 to 600 A, usual load-voltage rating 40 V, all sizes. A wide range of adjustments of welding current is provided in each size. The larger part of dc welding is done with this type of equipment.

Multiple-operator equipment and an adjustable series resistor for each arc circuit for operation from constant distribution systems are used to some extent. The special field for this equipment is where the service of each arc-welding circuit is infrequently in use, say, 25% of the time or less. In such cases the loss in the series resistor is less than the no-load loss of the single-operator unit for the same service.

Another type of dc-welding power source is a dry-type rectifier used in conjunction with a multiphase high-leakage-reactance transformer. Many of these rectifier-type welders use selenium rectifiers which are forced-air-cooled.

Rectifier-type welders are said to combine some of the desirable arcing characteristics of dc welding, such as easy arc starting, with those of welding transformers, such as reduced no-load losses. The same range of rating is available in rectifier-type welders used in rotating dc welders.

Alternating-Current Arc Welding. The field of ac arc welding is practically the same as that of dc arc welding.

The standard equipment for single-operator ac arc welding is a single-phase standard frequency transformer, sometimes with a number of voltage taps, and an adjustable reactance. Generally, capacitors are included to correct the power factor of the circuit to about unity between one-half and three-fourths load. The welding leads are limited to about 300 ft radius because of voltage drop.

Standard equipment includes ratings with the range of 150 to 1000 A, 30 to 40 V.

Atomic-Hydrogen Arc Welding. This method uses an ac arc between the tungsten electrodes (not including the work) in an atmosphere of hydrogen (shielded arc). Either commercial hydrogen or disassociated ammonia can be used. The weld metal is supplied by the base metal or, if additional metal is required, by a filler rod.

The method is very flexible. Practically any metal or alloy, ferrous and nonferrous, can be welded. Its greatest usefulness is for the fusion welding of certain ferrous alloys, for example, chrome-nickel steels, aluminum, and duralumin, but it must use flux to weld some of these materials. The welding of thin sheets, the production of tubing, and the repairing of expensive tools and dies are some of the common uses of the method.

Inert-Gas-Shielded Arc Welding. The method comprises the use of a single tungsten electrode, filler rod, and argon or helium as a gas shield. The particular field for the method is the welding of the light metals. No flux is required. The technique varies with the type of work. The following procedures are typical.

Welding aluminum and aluminum alloys—alternating current and argon

Welding magnesium and magnesium alloys—either alternating current and argon or direct current, reverse polarity, and either argon or helium

Welding stainless steel, mild steel, copper, and copper alloys—direct current, electrode negative, and either argon or helium or alternating current, high frequency, stabilized with argon or helium.

Consumable-Electrode Gas-Shielded Welding. This type of welding uses small, bare electrodes in coil forms. The welding is done in gas atmospheres. The 0.020- to 0.125-in.-diameter electrodes are fed mechanically into a handgun for manual welding at feed rates up to 1000 in./unit. The voltampere arc characteristics of this type of welding are rising. Standard dc welding generators do not give the best results. Special low-voltage dc welders give better results. The optimum characteristic is one which is rising, to match the arc characteristic.

Argon, argon and 1% oxygen, helium, and carbon dioxide or mixtures of these gases are used. Argon is used for welding aluminum, magnesium, copper alloys, and titanium. Argon-oxygen or carbon dioxide is used for mild-steel welding. Almost all welding is done with the electrode positive.

The automatic consumable-electrode gas-shielded equipment does not require elaborate control systems. With the low-voltage generators the current flow automatically regulates itself to burn off whatever amount of wire is being fed into the arc.

As a result of this type of welding the generator produces the current to make the burnoff of wire rate equal to the wire feed speed.

Direct versus Alternating Current. The considerations that affect the choice between direct current and alternating current are mainly the following:

1. Alternating current has a higher (85%) efficiency. Rotating direct current and rectifier direct current are about 65% under load. Also, no-load losses for rectifier direct current and alternating current are less than the no-load loss of the single-operator dc equipment. The saving is 25% to 30%. A larger saving may be made compared with multiple-operator dc equipment.
2. The power factor of alternating current and rectifier direct current is low (about 40% lagging) and can be corrected by the use of capacitors.
3. The magnetic deflection of the arc (magnetic blowout) is not so pronounced with the ac arc. This phenomenon is often troublesome in working with dc arcs of high current values. The ac arc permits higher current and larger electrodes in such cases, with a consequent higher welding speed.
4. The cost of electrodes must be compared.
5. The cost of equipment must also be compared.
6. Where the range of work in a shop is widely varied, the use of both types of arc welding may be found desirable.

Automatic Arc Welding. Automatic arc welding, either dc or ac, is confined mainly to simple joints which can be placed in the flat position for welding.

The electrode for direct current may be bare or coated. Coated electrodes for alternating current are usual practice except when the flux (in granular form) is applied to the work (submerged-arc method). Coated electrode wire in long lengths for feeding from a reel has a slot in the coating for electrical contact. Coated electrodes in short lengths with end contact are also used by adapting the feeding mechanism for automatic return to the starting position when the electrode is consumed.

The power-supply equipment, dc or ac as the case may be, for automatic arc welding is the same as for the corresponding manual operation.

The automatic regulator controls the rate of feeding of the electrode to match the rate of melting of the metal electrode by controlling the speed of the electrode motor in response to slight changes in the arc voltage so as to maintain a practically constant average arc voltage.

One type of automatic regulator in wide use is an electric device which contains the value and the direction of armature coil of a dc electrode motor. This control uses two thyatron tubes in the armature circuit of the electrode motor, passing current from an ac source in one direction or the other, as required, to feed the electrode up or down. The magnitude of the current passed is controlled by grid-phase shift

of the thyatron tubes in response to changes in the arc voltage in comparison with the preset reference voltage.

Automatic arc welding, a method independent of the human element in the operation, has many merits where it is applicable. The most important of these are uniform welds, high production rate, and low electrode loss. Also, a new trend is toward the use of robot welders with solid-state circuitry and logic control that perform repetitive functions and handle heavy production parts.

21.14.3 Induction Welding

Induction Resistance Welding. This method of welding incorporates the use of induction heating principles along with the application of high-frequency energy, usually in a radio-frequency range. It is particularly useful as a method of welding in tube mills. Here energy can be induced into the slit-formed tubing with a single-turn inductor and current caused to flow across the gap between pressure rolls where resistance welding is caused by the I^2R drop across the joint between the weld rolls.

This method of welding has been and is being used effectively for the welding of carbon steels, aluminum, copper, titanium, and mechanical stainless steel. This technique has been applied to portable weld units where it is possible to weld tubing and pipe on site from skelp.

The radio frequencies normally used for this type of welding are in the neighborhood of 200 to 450 kHz. It is possible to weld heavier wall material in this manner, frequencies being used in the neighborhood of 10,000 or even 3000 Hz, although these frequencies will not give as efficient an operating installation as the radio-frequency installation.

High-Frequency Resistance Welding. The application of contacts to line pipe utilizing radio-frequency energy has been successfully accomplished, and a weld similar to that obtained with induction resistance welding is thus secured. In this type of welding installation, high-frequency, preferably radio-frequency, energy is passed through sliding contacts to the V-shaped edges of the tubing. This current is then caused to flow across the contact between the pressure rolls, giving the I^2R heating effect of resistance welding at this point.

This method of welding is also effective on nonferrous materials, as well as carbon steels. It has been adapted to structural shapes and the finned-tube shapes.

Induction Butt Welding. Two properly faced tubular sections or rectangular sections butted together can be induction-heated with a suitable frequency. This work is dependent on the depth of penetration and the size of the part. The work is so heated that when the parts are brought to temperature they can be welded by the application of a suitable pressure. One of the members can be fixed and the other moved.

This method of welding has been particularly suitable for the welding of high-pressure boiler tubing, for the welding of railroad rails in the field, and for the butt welding of certain types of large cylindrical objects. Equipment has been furnished to weld transmission pipe in the field. A weld made in this manner is usually much faster than a weld made by a conventional electrical process.

Longitudinal Butt Welding. The longitudinal butt weld can be accomplished by induction on such mechanical equipment as a tube or pipe mill where hot-rolled skelp can be formed and welded continuously without the necessity of edge cleaning such as is required for conventional resistance welding. Of course, it is also possible to perform this type of welding by either induction resistance or high-frequency resistance welding.

21.14.4 Electron-Beam Welding

A method of welding, particularly in vacuum, has been developed which incorporates the utilization of an electron beam or beams for the welding of very thin and very narrow and unusual metals. This technique has been adapted to thin sections of conventional materials where it is desirable to obtain

a weld by heating a very narrow section of the parent metals and obtaining a bond as strong as the parent metal. Commercial units for this type of welding are available, and the units are applicable to certain production operations as well as to laboratory welding.

21.14.5 Electroslag and Plasma Welding

Electroslag welding is a welding process which relies on a molten slag which melts the filler metal and the surface of the work to be welded. The weld pool is shielded by this molten slag which moves along the entire cross section of the joint as welding progresses. The electrically conductive slag is maintained in a molten condition by its resistance to the current which flows between the electrode and the work.

This type of welding appears particularly suitable to replace multipass welding techniques. The process is especially applicable for welding plates ranging in thickness from 1¼ to 18 in.

This method may require welding current of the order of 55 to 65 A for ⅛-in-diameter electrodes; however, the range can vary depending on the material to be welded from 400 to 900 A.

The welding voltage required is normally in the neighborhood of 40 to 55 V for ⅛-in-diameter electrodes.

The electroslag method has been widely used in Europe for some time. Its use should be considered when the welding application involves large structural members, pressure parts in nuclear reactors, and high-pressure boiler downcomer tubes. It could be used for forged crank-shaft welding. It would be advisable in some instances to use it on press frames. It is suitable for cylinders for hydraulic presses, for turbines and alternator shafts, for rolling-mill frames, and for ship hulls.

Plasma is a field for electric heating now becoming commercially usable. There are basically two types of plasma heating: (1) arc plasma and (2) induction plasma.

Plasma heating involves the ionization of gases and develops extremely high temperatures.

Arc plasma heating has been used primarily for rapid melting of small quantities of material, both metals and refractories. It can be employed for cutting metals and is being used experimentally in investigations involving extremely high temperatures. A dc arc is generally used in obtaining the plasma.

Induction plasma heating is developed generally at frequencies of about 4 MHz. Experimentally, frequencies of 8 to 10 MHz have been utilized, and investigations are proceeding at many other frequencies. It is reported that plasma temperatures up to 20,000°F have been reached. Various gases are required, depending on the results desired. Gases commonly used are hydrogen, helium, argon, and nitrogen, and some work had involved the use of air.

21.14.6 Pressure Welding

Also called diffusion bonding or diffusion welding, the pressure-welding process is described as an atom-to-atom bond between two surfaces via intimate contact between their oxide-free surface areas. The surfaces must also be free of contaminants. To make the bond effective, the atoms on one surface must be brought, under pressure, within a few angstroms of the atoms of the second surface.

In some cases, interlayers of foil are necessary to achieve an adequate bond, acting as barrier layers between incompatible materials, to allow bonding of materials more readily welded at low temperatures, and to overcome problems with surfaces that have insufficient mobility to come into close contact.

Bonding is done in the solid state, with times and temperatures depending on the materials used. The method is advantageous because (1) it is applicable to a wide variety of joints; (2) many bonds can be made in one operation; and (3) bonds can be made in particularly hard-to-get-at places. At present, the disadvantage of diffusion welding is that joint assessment is difficult to make, but as technology improves, it is thought that, in the future, this type of welding may replace arc welding for major structural components such as nozzle and flange assemblies.

21.15 AIR CONDITIONING AND REFRIGERATION

21.15.1 Air Conditioning

The Air-Conditioning System. As described by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), an air-conditioning system maintains desired environmental conditions within a space. Air-conditioning systems are categorized by how they control cooling in the conditioned area. Typical central air-conditioning system applications include (1) spaces with uniform loads, (2) small spaces requiring precision control, (3) multiple systems for large areas, (4) systems for complete environmental control, and (5) a primary source of conditioned air for other subsystems. Spaces with uniform loads are generally those with relatively large open areas and small external loads, such as theaters, auditoriums, department stores, and the public spaces of many buildings. Isolated rooms within a larger building with cleanrooms and computer facilities will typically require precision control. Large buildings such as factories, airplane hangers, shopping malls, office buildings, and hospitals require multiple systems.

Environmental Concerns. Owners of many medium-size and most large buildings find it more economical to cool their buildings by distributing chilled water to remote air-handling units than use large space-consuming air ducts from a central air handler. As a result, electric centrifugal chillers are used extensively for cooling commercial buildings. These chillers use chlorofluorocarbons (CFCs) as a refrigerant, and represent a class of extremely stable chemical compounds that are non-toxic and inexpensive. International agreements have been made to phase out use of these chemicals, primarily as a response to the concern that the CFCs may be contributing to the depletion of the ozone layer in the upper atmosphere and to global warming. Other refrigerants are available that limit or eliminate this problem, hydrochlorofluorocarbons (HCFCs), which have one or more hydrogen atoms in their structure and therefore decompose much more readily in the lower atmosphere, and hydrofluorocarbons (HFCs), which contain no chlorine and have little impact on stratospheric ozone.

Substitute refrigerants are available for many CFCs used in chillers. HCFC-123 is the present substitute for CFC-11 (R-11) in chillers, and for CFC-12 (R-12) chillers the substitute is HFC-134a. But neither refrigerant is a “drop in” substitute on existing equipment. Only in cases where equipment is relatively new and is specifically designated “compatible” with the new refrigerants can the substitution be easily made. In most cases, however, new equipment must be purchased that has been designed to use these substitutes. Availability of this equipment is increasing, and the new units can be supplied with performance equal or very close to their CFC counterparts.

Alternatives to electric chillers include steam and gas direct gas-fired absorption chillers, and gas engine-driven chillers. In a specific installation, the engineer must be careful to consider all costs with each alternative and compare options on an equitable, life-cycle cost basis.

Psychrometric Formula. A major step toward the development of air conditioning as a science was made by Willis H. Carrier with the derivation of the rational psychrometric formula (*Trans. ASME*, 1911) which established the relationship between dry-bulb and wet-bulb temperatures, both easily ascertainable, and other important properties of the air such as density, relative and absolute humidity, vapor pressure, and total heat, the exact valuation of which is essential to the solution of problems involving the exchange of heat and humidity between air-conditioning apparatus and conditioned spaces and their contents. The rational psychrometric formula is the basis for numerous psychrometric charts.

Psychrometric Terms

Dry-bulb temperature is the commonly observed temperature of the air as indicated by a conventional thermometer not affected by the relative humidity of the air.

Wet-bulb temperature is the temperature of adiabatic saturation of air or the temperature at which air would normally saturate without any change in its heat content. Wet-bulb temperature is,

therefore, also a measure of the total heat content of air; that is, at a given wet-bulb temperature the total heat is constant regardless of changes in the dry-bulb temperature.

Relative humidity within the normal range is the percent ratio of the weight of water vapor actually contained in a unit of space to the weight of water vapor that the same unit of space would contain if fully saturated at the same dry-bulb temperature.

Absolute humidity is the actual weight of water vapor in air at any given condition and is usually expressed in grains per cubic foot or grains per pound of dry air.

Dew point is the temperature of saturation of air, or the point beyond which any further reduction in temperature would result in condensation.

Effective temperature is an arbitrary index of the degree of warmth or cold felt by the human body in response to temperature, humidity, and air motion. Experimentally determined, the scale has been fixed by the temperature of saturated air which reproduces the sensation of warmth felt at other combinations of conditions.

Sensible-heat effect is the exchange of heat between air and its surroundings or apparatus that changes the dry-bulb temperature without affecting the moisture content. It is convenient to consider sensible heat as dry heat.

Latent-heat effect is the exchange of moisture between air and its surroundings or apparatus by evaporation or condensation resulting in a change in the moisture content of the air with consequent change in the total latent heat of vaporization represented by the moisture in the air. It is convenient to consider latent heat as humidity.

Comfort Cooling. Investigations carried on under the auspices of the American Society of Heating and Ventilating Engineers (ASHVE), now ASHRAE, indicate that effective temperatures varying from 70 to 73°F are acceptable inside conditions for peak summer weather depending on length of occupancy and for normally clothed, normally active commercial workers. Table 21-8 gives approximate dry-bulb temperature and relative-humidity combinations within normal range which produce effective temperatures within the stated range with air motion 15 to 25 ft/min.

Inside design conditions of 78 to 80°F dry bulb with 45% to 55% relative humidity, depending on the character of occupancy, are accepted as standard inside design conditions against peak outside conditions for commercial comfort-cooling applications in almost all parts of the United States.

It is seldom desirable to design for inside temperatures in excess of 80°F. It is generally impracticable to reduce the humidity sufficiently to produce effective temperatures within the desired range at dry-bulb temperatures much in excess of 80°F.

TABLE 21-8 Inside Design Conditions

	Relative humidity, %		
	45	50	55
Effective temperature	Dry-bulb temperature, °F		
73	79½	79	78
72	78½	77½	77
71	77	76½	76
70	76	75	74½

Note: $t_c = (t_F - 32)/1.8$.

Industrial-Process Air Conditioning. In industrial or process air conditioning, inside design conditions are frequently dictated entirely by the product requirements. In confectionery plants where chocolate is handled, it is usually not desirable to have temperatures in excess of 65°F (dry bulb), which is far below the comfort range. In chemical or pharmaceutical plants where deliquescent chemicals are handled, lower-than-average humidities may be required for satisfactory production. Many products can be satisfactorily processed at widely varying conditions as long as the condition is maintained constant and the process adjusted to it.

Where conditions are established by product requirement, design is usually directed toward maintenance of satisfactory working temperatures. Investigations to determine the limits for optimum health and efficiency of the industrial workers indicate that conditions should not exceed 80°F

effective temperature, that is, approximately 82.8°F, dry bulb at 80% RH, 84.4°F D at 70% RH, 86.2°F D at 60% RH, 88.2°F D at 50% RH, and 90.3°F D at 40% RH. Lower effective temperatures are required where perspiration must be prevented to avoid contamination or staining of products during handling.

There has been a marked increase in the use of complete air conditioning, including refrigeration, even in industrial operations where atmospheric control is not required by the process involved. An example is the trend toward larger manufacturing areas under single roofs, where windows cannot be depended on for light or ventilation. In many cases it has proved less expensive in both first cost and operating cost to provide full air conditioning with refrigeration rather than ventilation.

Winter Heating. Winter heating systems for normally occupied interiors are almost universally designed to maintain 70°F inside, with outside conditions assumed at 10°F above the lowest recorded temperature for the district in question.

Maximum Outside Design Conditions. These are usually taken at values which will not exceed 2.5% of the total hours during June, July, August, and September. Accepted maximum design dry-bulb (D) and wet-bulb (W) temperatures in degrees Fahrenheit for larger cities representative of various climatic divisions of the United States are given in Table 21-9.

Cooling Load. Calculation of the cooling load involves consideration of all possible internal as well as external heat gains not only for transmission and infiltration but also from sunlight radiation.

Solar Heat. Sunlight radiation for 40°N latitude on July 21 attains maximum values in Btu per square foot per hour transmitted by unshaded glass for variously oriented surfaces as follows: east, 200 at 8 A.M.; south, 91 at 12 noon; west, 200 at 4 P.M.; horizontal 258 at 12 noon (*ASHRAE Guide and Data Book*). Major consideration must be given to sun-exposed glass. Of the total impinging radiation, the amount passing through the net area of the window is approximately as follows: unshaded, 100%; half covered by buff shade, 70%; fully covered by light-finish venetian blinds, 70%; equipped with canvas awning, 30%. Although sunlight-radiation effect on walls and roofs can be calculated, allowance is usually made for this effect by calculating heat transmission at a temperature above the design outside temperature. A substantial temperature head (usually 50°F) should be allowed in calculating transmission through the roof surface due to long hours of exposure to the sun. Heat from sunlight contributes only to the sensible-heat load.

Heat Transmission. Transmission of heat through the structural surfaces of buildings or spaces is directly proportional to the temperature difference between the two sides of the surface and to the thermal conductivity of the material or materials forming it. Overall coefficients for a number of common structural elements are given in Table 21-10. The coefficient *U* is expressed in Btu per hour

TABLE 21-9 Maximum Summer Design Conditions

City	D	W	City	D	W	City	D	W
Boston	88	74	Cleveland	89	75	Seattle	80	65
New York	93	76	Chicago	91	76	San Francisco	77	62
Philadelphia	90	77	St. Louis	94	78	Los Angeles	90	70
Washington, D.C.	92	77	Atlanta	92	77			
Jacksonville	94	79	Birmingham	94	78			
New Orleans	91	80	Dallas	99	78	Denver	90	64
Houston	94	80	Phoenix	106	76	Salt Lake City	94	66

Source: ASHRAE Guide and Data Book.

TABLE 21-10 Coefficients of Heat Transmission U
Surface composition

Single window	1.13
Double window	0.56
12-in brick wall, no interior finish	0.35
12-in brick wall finished with 3/4-in plaster on metal lath, furred	0.25
10-in hollow-tile wall, stucco exterior, no interior finish	0.33
10-in hollow-tile wall, stucco exterior finished with 3/4-in plaster on metal lath, furred	0.24
10-in concrete wall, no interior finish	0.61
10-in concrete wall finished with 3/4-in plaster on metal lath, furred	0.36
Wood siding, 1-in sheathing, studs, 3/4-in plaster on metal lath	0.26
Wood siding, 1-in sheathing, studs, 3/4-in plaster on metal lath, 3-in rockwool fill	0.07
Double partition, metal lath and 3/4-in plaster on both sides of studding	0.39
4-in hollow-tile partition, plastered on both sides	0.37
Yellow-pine flooring (25/32 in) on joists, no ceiling	0.45
Yellow-pine flooring (25/32 in), 3/4-in plaster on metal-lath ceiling below joists	0.31
6-in concrete slab floor, 1/4-in asphalt tile, no ceiling	0.60
6-in concrete slab floor, 1/4-in asphalt tile, 3/4-in plaster on metal lath hung or furred ceiling	0.38
1-in wood flat roof, built-up roofing, no ceiling	0.48
1-in wood flat roof, built-up roofing, 3/4-in plaster on metal-lath ceiling below joists	0.33
1-in wood flat roof, 1-in rigid insulation under built-up roofing, no ceiling	0.21
1-in wood flat roof, 1-in rigid insulation under built-up roofing, 3/4-in plaster on metal-lath ceiling below joists	0.17
4-in concrete-slab flat roof, built-up roofing, no ceiling	0.70
4-in concrete-slab flat roof, 1-in rigid insulation under built-up roofing, no ceiling	0.24
4-in concrete-slab flat roof, built-up roofing, 3/4-in plaster on metal-lath ceiling, hung or furred	0.41
4-in concrete-slab flat roof, 1-in rigid insulation below built-up roofing, 3/4-in plaster on metal-lath ceiling, hung or furred	0.18

Source: ASHRAE Guide and Data Book.*Note:* 1 in = 25.4 mm.

per square foot per degree Fahrenheit temperature difference across the surface and is based on an outside-surface coefficient for 15-mi/h wind velocity.

Total heat transmission through any exposed building surface may be computed by the formula

$$H = A \times U(t_o - t_i) \quad (21-21)$$

where H = sensible heat in Btu per hour, A = area of the surface element in square feet, U = coefficient of heat transmission of the surface, and t_o and t_i are, respectively, the outside and inside temperatures in degrees Fahrenheit. This formula is used for computing heat loss from a space as well as heat gain to it.

Heat from Occupants. Every occupant of a conditioned space contributes both sensible and latent heat to the atmosphere; the relative proportions is dependent on the dry-bulb temperature and the total quantity on the state of activity of the individual (see Table 21-11).

Only the sensible heat(SH) fraction affects the temperature of the conditioned space, since latent heat (LH) from evaporation of body moisture appears as vapor at room temperature.

Electrical Heat. The heat equivalent of the electrical input to all lights and electrical heating or power appliances used within a conditioned space contributes to the atmospheric heat which must be removed by the air-conditioning apparatus. In general practice, the approximate heat equivalent of

TABLE 21-11 Heat Loss from Average Person, in Btu per Hour, as Sensible Heat (SH) and Latent Heat (LH)

		Dry-bulb temperature, °F					
		70		75		80	
		Segregated heat loss, Btu/h					
		SH	LH	SH	LH	SH	LH
Condition of activity	Total heat loss, Btu/h	SH	LH	SH	LH	SH	LH
Seated at rest	400	300	100	260	140	220	180
Light work	660	350	310	290	370	220	440
Moderate work	850	430	420	360	490	270	580

Note: 1 Btu/h = 0.293 W; $t_{c} = (t_F - 32)/1.8$.

3400 Btu/h · kW input to lights and appliances and 2500 Btu/h · hp of motor capacity is used in calculating heat gain from this source. In considering heat from appliances and motors, load factor should be carefully investigated, since appliances or motors seldom run continuously at full load. Unless appliances are used for water heating or evaporation, the entire load from electrical sources will be sensible heat.

Process Heat. Heat from gas appliances is the most common form of process heat. Average heat input to common gas appliances in Btu per hour is as follows: 14-in coffee urn, 7500; 12-in coffee urn, 5000 (*ASHRAE Guide and Data Book*). Heat output will be approximately 75% sensible heat and 25% latent heat. Consideration should be given to load factor of appliances.

Ventilation and Infiltration. Air quantity for ventilation purposes is usually based on the number of occupants of the conditioned space. Ventilation is required chiefly to overcome normal odors. Average accepted practice calls for the introduction of at least 10 ft³/min of outside air for each non-smoking occupant and 20 ft³/min for each smoking occupant. For commercial interiors, such as restaurants and drugstores, where moderate smoking occurs, 15 ft³/min per person is usually allowed. In theaters, where ceiling heights are usually liberal, where there is no smoking, and peak occupancy seldom occurs for long periods, an allowance of 7½ ft³/min per peak occupant is considered ample. Air positively exhausted from a space must be deducted from the positive ventilation supply in considering possible infiltration. If the exhaust exceeds the supply, infiltration will naturally be induced. Air for ventilation should be first brought to the conditioning apparatus and conditioned before introduction to the conditioned space.

Infiltration varies with the construction, exposure, and size of a conditioned area as well as with door traffic and location of doors. The following quantities are suggested as a general guide for buildings of average construction: cubical contents 0 to 5000 ft³, one complete change of volume in 30 min; 5000 to 50,000 ft³, 40 min; 50,000 to 100,000 ft³, 60 min; 100,000 to 200,000 ft³, 90 min; over 200,000 ft³, 120 min. Infiltration in cubic feet per minute for load calculation and comparison with positive supply in cubic feet per minute may be determined by dividing cubical contents of the space by the time factor for that space magnitude.

The sensible-heat component of ventilation or infiltration may be computed approximately from the formula

$$H_s = Q \times 1.07(t_o - t_i) \quad (21-22)$$

where H_s = sensible heat in Btu per hour, Q = cubic feet per minute of air, and t_o and t_i = outside and inside temperatures in degrees Fahrenheit, respectively.

The latent-heat component of ventilation or infiltration may be computed approximately from the formula

$$H_L = Q \times 0.675(h_o - h_i) \quad (21-23)$$

where H_L = latent heat in Btu per hour, Q = cubic feet per minute of air, and h_o and h_i = outside and inside absolute humidities, respectively, expressed in grains per pound of dry air (see a psychrometric chart).

Only infiltration air entering the conditioned space directly contributes to the internal heat load. Ventilation air-conditioned before introduction to the space contributes to the load upon the conditioner and cooling apparatus only.

The Internal Sensible-Heat Load. This will be the summation of the sensible heat from transmission, sunlight radiation, occupants, lights, electrical devices, process heat, and infiltration. The *internal latent-heat load* will be the summation of the latent heat from occupants, process heat, and infiltration. A factor of safety of 10% is often added to these figures to allow for inaccuracies and, in the case of sensible-heat load, to cover the power input for air circulation. The *total heat load* on the conditioner or cooling apparatus will be the sum of the internal sensible- and latent-heat loads plus the sensible- and latent-heat load of ventilation air. Grand-total heat is usually expressed in tons of refrigeration effect.

Air Quantity for Sensible-Heat Absorption. The sensible-heat load usually serves as the first guide to the selection of proper air quantity. The specific heat of air within the normal air-conditioning range is approximately 0.241 Btu/lb · °F. One Btu will raise 4.16 lb of air 1°F, or approximately 56 ft³ of air 1°F. The air quantity required to absorb a given sensible-heat quantity may be determined by the formula

$$Q = \frac{H_s}{60} \times \frac{56}{t_i - t_d} = \frac{H_s}{1.07(t_i - t_d)} \quad (21-24)$$

where Q = air quantity in cubic feet per minute, H_s = sensible heat in Btu per hour, t_i = space temperature in degrees Fahrenheit, t_d = delivery temperature of air into the conditioned space in degrees Fahrenheit, 60 = minutes per hour, and 56 = cubic feet per Btu per degree Fahrenheit temperature rise. Modern diffusion-type outlets will permit satisfactory delivery of air into spaces of 10- to 12-ft ceiling at 60°F. With higher ceiling heights and good conditions, air may be introduced at 55 to 50°F.

Latent-Heat Absorption (Dehumidification). For the quantity of air selected to meet the sensible-heat load by the method just suggested, the moisture content at which the air must be introduced into the space to absorb the internal latent-heat load may be approximately calculated by the following formulas:

$$h_r = \frac{h_L}{Q \times 0.675} \quad \text{and} \quad h_d = h_i - h_r \quad (21-25)$$

where h_r = humidity deficiency in grains per pound of dry air; h_d and h_i = absolute humidity in grains per pound of dry air at delivery condition and within the room, respectively; H_L = internal latent heat in Btu per hour; Q = air delivery in cubic feet per minute; and the factor 0.675 is calculated from the average density of air, the average latent heat of moisture in Btu per grain, and rate correction. The delivery-moisture condition thus calculated, together with the delivery temperature, will permit graphical determination of the required delivery-air conditions from a psychrometric chart. *Dehumidification* is usually accomplished by condensation of moisture in the process of cooling the air.

Cooling-Dehumidifying Apparatus. Two types of apparatus are used for cooling and dehumidifying: (1) the spray-type dehumidifier and (2) the surface cooling coil. In either, cooling and dehumidification may be accomplished by cold fluid at the proper temperature from any source, for example, cold water from wells or ice tanks or water cooled directly by refrigeration apparatus or by the direct expansion of refrigerants in cooling coils.

Spray Type. In the spray-type dehumidifier, air to be conditioned is passed through a spray chamber into which a large volume of finely divided water is introduced. Spray-type dehumidifiers are of two general types: (1) those in which water cooled externally is introduced at a reduced temperature and (2) those in which water is sprayed over coils cooled by fluid from an external source.

Spray-type dehumidifiers have the advantage of permitting evaporative cooling of cleaning the air of siliceous dust, and of absorbing some gases and odors.

Surface Cooling Coils. Surface cooling coils are widely used for cooling and dehumidification. Cooling of surface coils is usually accomplished by direct expansion of refrigerant though frequently cold water or brine is used.

Common designs include (1) pierced-plate types in which the tubes pass through closely spaced thin metallic plates, (2) helical extended surface in which a ribbon of metal crimped or slit to accommodate curvature is wound in a helix about the central tube, and (3) the type in which fins are extruded directly from the tube body by rolling.

Heating Surface. Heating surface is generally similar to cooling surface in construction. Extended cast-iron surface is still used to some extent. Steam is an accepted heating medium, although the use of hot water is increasing, as it facilitates control.

Humidification and Humidifiers. In many comfort cooling applications and some industrial-process operations which have low winter heat loads and require only moderate humidification during the winter, this is accomplished by small sprays which introduce finely divided water droplets into the air stream usually directly before or after the heating coil so that evaporation is stimulated. Pan-type humidifiers in which water is evaporated into the air stream by steam coils or direct steam sprays may also be employed. It should be noted, however, that these procedures add to the loading within the space and therefore should be employed only where there is a deficiency in heat gain or a heating requirement.

In large commercial or industrial operations employing spray-type air washers for summer cooling and dehumidification, humidity control is usually achieved by maintaining a constant dew-point temperature and then allowing the air to rise to the dry-bulb temperature, resulting in the desired final relative humidity in absorption of heat gains within the space. It should be noted that the majority of industrial and many large commercial applications involve internal loading from power, lights, etc., which require the application of cooling during all seasons of the year when there is normal occupancy or operation. During winter this cooling may be obtained by outside air, as described subsequently for evaporative cooling, but there is no heating requirement during normal service.

The major shortcoming of the dew-point control method for humidity maintenance lies in the fact that there must be a fixed relationship between the maintained dew point and the final dry-bulb condition within the space to achieve the desired relative humidity. Thus there is a fixed relationship between the load and the temperature rise in supply air which may be taken to absorb this load, and this relationship may result in the requirement for excessively high circulating-air quantities, particularly if high relative humidities must be maintained as is common in many textile-mill operations.

Accordingly, in such operations where high relative humidities must be maintained with high continuous internal heat loads, common practice is to employ a *split system* in which the dew point of the circulating air is maintained at an arbitrarily low level which would normally result in insufficient humidification after absorption of the heat load, but the humidity is increased within the space by the direct application of water droplets from compressed-air or motor-operated mechanical atomizers. The atomized moisture introduced directly into the space is in water form and in the process of evaporation not only increases the relative humidity but also absorbs sensible heat from the space in the process of being converted from water to vapor at the room condition. The moisture thus introduced does not add anything to the heat load within the space and further, by the process noted above, increases the sensible-heat-absorbing capacity of the primary supplied air, thus making it possible to perform the required cooling with a substantially lower volume of circulating air than would be needed for the straight dew-point method.

Atomizers are also frequently used as prime means for humidification in areas such as textile mills. Employed in this fashion or with the central-station system, they also afford an excellent facility for direct humidity control in zones within a major area.

Evaporative Cooling. During intermediate seasons in normal climates or in climates such as prevail in dry mountainous country where temperatures are frequently excessive but humidities continuously low, evaporative cooling systems are very effective. Air is saturated adiabatically and thus

assumes the wet-bulb temperature. Sensible cooling is thus done at the expense of increased humidity. Calculations for evaporative cooling systems are identical with those for other cooling loads except that 100% outdoor air is used.

Commercial evaporative coolers are similar to spray-type washers or humidifiers or spray-type dehumidifiers. The spray water is continuously recirculated by means of a pump.

Fans for Air Conditioning. Many different types of fan are used in HVAC systems, each of which has certain advantages. Centrifugal fans generate pressure by accelerating air outward from a fan wheel and then converting this kinetic energy to pressure. Centrifugal fans are able to generate relatively high pressures, but tend to be large and heavy with high WR^2 loads. Axial fans, on the other hand, generate pressure using the lift created by the fan blades much like a propeller. Axial fans generate high flowrates at low pressures and have low rotating-mass characteristics. In general, axial fans have to rotate much faster than do centrifugal fans to generate comparable pressures and flow rates. As a result, they tend to generate higher airborne noise levels. However, their lower weight and space requirements make axial fans preferable to centrifugal fans for many ventilation applications. Their high rotating speed requirements are also suitable for direct drive by 4-pole and 6-pole induction motors. By eliminating the belt, these fans are more compact and energy-efficient because of the avoided losses in the belt drive.

In residential applications, the forward-curved-blade centrifugal fan is commonly used because of its ability to generate pressure and flow at relatively low operating speeds. This low-speed operation allows forward-curved fans to generate low noise and structural vibrations. However, in general, forward-curved fans are relatively inefficient, and are not used in larger applications where long operating times can incur high energy costs. Residential HVAC fans are usually powered by single-phase, multispeed motors.

In many commercial applications, backward-inclined centrifugal fans are used to move large amounts of air. When equipped with airfoil-shape blades, these fans can achieve high operating efficiencies. In systems that are distributed over a large floorspace, smaller fans are installed throughout the system ductwork to boost air pressure to the points of delivery.

In many industrial applications, fans also serve to exhaust contaminants and to provide convective cooling by circulating air within a workspace. In simple applications, basic propeller fans are installed without ductwork in rooftops to remove inside air. In more complex applications, fan selection is based on the size, configuration, and pressure requirements of the ventilation system, air properties, contaminant levels, and number of operating hours. Radial-blade and radial-tip centrifugal fans are used in ventilation applications with high particulate levels. The shape of these blades prevents the accumulation of contaminants on the blade surfaces.

In emergency ventilation systems, fan operation is relatively infrequent; consequently, tubular axial fans are often used because of their low starting torque requirements and their space saving features. Most industrial HVAC fans are driven by NEMA Design B polyphase induction motors. Service factors for centrifugal and axial fans are typically 1.10 to 1.15.

Fans are commonly connected to V-belt drives. By using different pulley sizes between the motor and the fan, belt drives allow fans to rotate at slower speeds than their motors. Most fan motors are 2-pole, 4-pole, or—in some cases—6-pole, which rotate at 3600, 1800, and 1200 rpm, respectively. In many HVAC applications, multispeed motors allow the selection of two of these speeds. By using a larger pulley on the fan than the motor, the fan rotates at a lower speed, reducing noise and vibration levels. Speed reduction ratios range between 1–1.5 and 1–4.

Adjustable-Speed-Drive (ASD) Applications. In ventilation systems, the larger opportunities for energy improvement are through the use of variable-speed drive fans and variable-air-volume systems. *Variable-air-volume* (VAV) systems rely on the use of dampers at the point of air delivery to control the amount of heating or cooling air entering a space. VAV systems are improvements over previous system designs such as dual-duct and reheat systems. Dual-duct systems mix cool and warm air streams to achieve a desired delivery temperature. Reheat systems cool air to temperatures between 45 and 60°F, to remove moisture, then reheat it to the desired delivery temperature. Unlike VAV systems, which avoid the unnecessary heating and cooling of air, dual-duct and reheat systems are relatively energy inefficient. Adjustable-speed drives are well suited to operate with the circulating

fans in VAV systems, can control the operating speed of a fan to regulate airflow, and can be equipped with feedback instrumentation that matches fan speed to system airflow requirements. By slowing fan speed during periods of low system demand, ASDs minimize the amount of excess flow energy imparted to the system.

Variable-frequency drives (VFDs) are the most common type of ASD. VFDs rely on rectifiers and inverters to adjust the frequency of the power delivered to the motor. VFDs can be combined with direct-drive units to offer attractive advantages in speed control, efficiency, and space savings. VFDs are widely used in commercial and industrial applications, and are included with up to 10% of all new fan installations.

Automatic Control. Most control devices depend on physical, thermal, or hygrostatic force for their operation. For example, thermostats frequently are operated by the distortion of bimetallic strips caused by the unequal expansion of the metals with increase in temperature or by the increase in pressure with rise in temperature of a liquid or gas contained in a closed element. Hygrostats generally depend on the expansion or contraction of human-hair strands with changes in humidity to perform the basic control operation, although silk, paper, or wood is used in certain applications. The thermostatic and hygrostatic elements usually operate other devices to perform the control operation.

Air-Conditioning Control Equipment. This equipment may be divided into three separate classes: self-contained, pneumatic, and electrical.

Self-contained devices are usually composed of thermostatic-fluid elements directly operating steam, water, or brine valves. These devices are not used where close control is necessary or where instantaneous tight shutoff is required. However, they are simple, cheap, and reliable and inherently give modulated control.

Pneumatic-control systems are those in which the thermostatic or hygrostatic element controls the rate of air leakage from a compressed-air system. The air pressure in the control system is used to operate diaphragm motors controlling valves and dampers. The spring loading of these motors can be varied so that within the given control-pressure range a whole sequence of separate valve and damper operations can be accomplished. Various types of relay and compensating arrangements are used to overcome inherent tendencies of such systems to override or "hunt" if set for high sensitivity or to give too wide a control range if set for low sensitivity.

The most common *electric thermostatic or hygrostatic controls* are of the *snap-action type*; that is, the condition change simply serves to cause the device to make or break an electric circuit, which in turn controls the major element or elements to be operated. Because of contact difficulties, line-voltage controllers generally use mercury-tube contactors, which limit the accuracy of control. All wiring to the control must be run in conduit. Low-voltage controls (24 V ac) which operate major motor drives or other elements through relays are more common; the light, open contacts permit accurate control, and open wiring (usually metal-clad) is allowed.

Electric controls employing thermocouples or resistance thermometers for sensing temperature conditions and various electrical leakage devices to determine humidity conditions are finding extensive application for air-conditioning control. However, for large-system work in the actuation of valves and dampers it is hard to find a satisfactory substitute for the pneumatic or hydraulic operator, so that electric or electronic control circuits usually act through other relays to actuate the major system elements by means of such operators. Nevertheless, there is an increase in the use of electric and electronic equipment because of the trend to centralizing main control observation, recording, and actuating points as a result of the complexity and extent of the systems being installed in large commercial and industrial operations.

Air-Conditioning Systems. *Central systems* are usually assemblies of air-conditioning apparatus designed to afford the necessary atmosphere control and may be arranged with (1) a single fan and single apparatus to care for one space; (2) two or more fans and a single apparatus to care for two or more zones; (3) a single fan blowing through warm and cool air chambers with mixing dampers delivering properly proportioned air to two or more zones; (4) a single apparatus and central fan

delivering highly conditioned air to individual recirculating fans in two or more zones; or (5) a single central apparatus and fan with supplementary cooling or heating equipment in the ducts leading to two or more zones.

The wide application of air conditioning to multiroom, multistory commercial structures presents a number of problems which have resulted in the development of a number of new systems and techniques. Among systems in common use are the following:

1. The fan-coil system which employs individual units served with hot or cold water from a central circulating system or zone.
2. The high-pressure induction unit system where highly conditioned air at a high velocity is used to aspirate the flow of room air through localized heat-transfer coils supplied with hot or cold water from an external source, the primary air caring for ventilation and dehumidification while the secondary coil cares for the major sensible-heat gain or loss within the zone.
3. The low-pressure hot and cold plenum system in which each zone is supplied from a central unit or apparatus where warm and cold air are mixed as required to meet the zone demand.
4. The high-pressure double-duct system in which warm and cold air from central apparatus served through parallel trunk supply systems are mixed at a local distributing point in each zone through a sound-deadening mixing-valve device subject to control from the immediate zone.
5. The single-effect high-pressure interior system for substantial areas with relatively constant load characteristics with control for various sections by manual or automatic volume regulation, etc.

The Unit Air Conditioner. This is a factory-assembled system within a suitable casing of component apparatus necessary for atmosphere control which may include filters, sprays, cooling or heating coils, fan motor, dampers, etc. Unit air conditioners which include in the same casing the refrigerating system are defined as *self-contained unit air conditioners*. *Direct units* are those designed for location within the conditioned space. *Indirect or remote units* are those which are designed for location outside the conditioned space. *Free-delivery units* are those with fixed fan characteristics designed for use without air ducts.

Self-contained room air conditioners designed for mounting in a window or special opening through an outside wall have been highly developed as a plug-in appliance requiring only electrical connection. These units consist of filter and cooling coil, conditioned-air fan, and outlet and inlet grilles, together with refrigeration compressor, motor and drive, condenser air fan, and air-cooled condenser, the latter elements located outside the building wall.

These units are available with total heat-removal capacities in Btu per hour ranging from approximately 5000 to 24,000 and with nominal power input approximately 1 hp/10,000 Btu capacity. Units up through 8000 Btu capacity are generally suitable for operation on 115-V single-phase service. Larger units usually require 230-V single-phase service, but this is available for such use in most areas. Units of this type almost universally employ air-cooled condensers.

Self-contained commercial units with the refrigeration system built in as part of the factory assembly are manufactured in various sizes with nominal total heat-removal capacities ranging from 2 tons to in excess of 30 tons. Units in capacities of 2 to 10 tons are frequently employed as direct units within the space, and many employ water-cooled condensers. However, the current trend is to air-cooled condensers located external to the space. A number of designs are available in capacities ranging from 5 to 30 tons designed for roof mounting and complete with air-cooled condensers and in many instances with electric-resistance heating coils or automatic gas or oil-fuel burner systems for heating. Such units are sometimes used in multiple to take care of fairly substantial commercial or industrial areas in single-story construction.

Self-contained and factory-assembled condensing units complete with either water- or air-cooled condensers and suitable for connection to remote air-conditioning units are currently available in capacities of 2 to 75 tons.

Drives for Air-Conditioning Systems. There is no satisfactory substitute for electric-motor drive for the power auxiliaries of air-conditioning systems. Compression-refrigeration systems which are

used in conjunction with the large majority of air-conditioning installations are primarily designed for electric-motor drive.

Fuel and Energy Conservation. Because of the rising cost of fuels and energy, and the rapid rate at which fossil fuels are being used, methods of energy conservation are being emphasized. Some of these include

1. *Use of computer programs* to determine the efficient energy use of the building or plant. Massive data relating to constants and variables, such as building occupancy, fuel consumption, and electrical characteristics of the building, are fed into the computer and compared with programs to conserve fuel. An analysis of the comparison shows which proposals are feasible and which are not.
2. *Automated monitoring* of key systems; for example, logic controllers can be set up on boilers to ensure efficient fuel utilization automatically.
3. *Heat-recovery systems.* Heat-recovery cooling units are growing in popularity; typical systems can be water-to-air or air-to-air types. Heat is recovered from areas of a building or plant that requires cooling and transferred to a portion of the plant that requires heating. Some systems recover flash steam for building heating, and still other systems can turn a dust-collection unit into a heating system by filtering the dust and particles through a hopper into drums for disposal, while redirecting the clean filtered air into the plant or building for heating.
4. *Solar air conditioning, heating, and cooling.* Solar collector arrays and reflector panels are located on a building's roof and are capable of regulating and storing the energy received from the sun for equal distribution during the day.

21.15.2 Refrigeration

Refrigeration Cycles. All practical refrigeration cycles produce heat removal by free evaporation in an enclosed chamber (evaporator) of a liquid (refrigerant) under pressure conditions that produce the desired evaporation temperature. The refrigerant liquid absorbs its latent heat of vaporization from the medium being cooled and in this process is converted to vapor at the same pressure and temperature. This vapor is conveyed to another chamber (condenser), in which the pressure is maintained at a level sufficiently high to permit condensation of the refrigerant by water or air at normal temperatures. The heat quantity abstracted in the condenser is the latent heat of condensation (or vaporization reversible) of the refrigerant fluid, together with the heat that has been added to the refrigerant in the process of conveying it from the evaporator pressure level to the condenser pressure level. The condensed refrigerant (liquid) is allowed to flow from the condenser, through suitable throttling valves, back to the evaporator to repeat the cycle.

Unit of Refrigeration. The standard unit of refrigeration is the ton, which is considered as heat removal at the rate of 200 Btu/min or 12,000 Btu/h or 228,000 Btu/24 h. This rate of cooling is about equivalent to the average cooling effect obtained by melting 1 ton of ice in 24 h at 43°F (latent heat of fusion of ice is 144 Btu/lb).

Refrigeration Systems. Practical refrigeration systems differ only in the method used to convey the refrigerant vapor from the evaporator, or low side, to the condenser, or high side. In closed refrigeration systems, three methods are used to accomplish this transfer: (1) mechanical compression or pumping of the refrigeration vapor, (2) chemical absorption of the refrigerant vapor at low pressure with subsequent transfer to the high side as solute in a solution, and (3) physical absorption of the refrigerant vapor at low pressure with subsequent transfer to the high side as adsorbed vapor in a solid. Related to systems (2) and (3) are absorption and adsorption dehumidification systems used in air-conditioning processes requiring drying of air without cooling it.

Compression-Refrigeration Cycle. In the compression-refrigeration cycle a mechanical compressor or pump is used to convey the refrigerant vapor from the (low) evaporator pressure to the (high)

condenser pressure. Vapor is drawn from the evaporator, where it has been evaporated in performing the cooling work, and is compressed and delivered to the condenser where it is liquefied, its latent heat of vaporization being absorbed by the condenser-cooling medium, which is usually water or air at normal temperature. The liquefied refrigerant is collected in the bottom of the condenser or in a separate container called a "receiver" and from there is fed back to the evaporator through suitable throttling valves.

There are three types of mechanical compressor in common use: (1) the reciprocating compressor, (2) the rotary compressor, and (3) the centrifugal compressor. To these must be added the jet compressor, which, while not usually considered as a mechanical compressor, is quite similar in operation. The *reciprocating and rotary compressors* are positive-displacement compressors; that is, each cycle of the compressing member definitely opens a fixed volume into which fluid flows and then closes or occupies that same volume, forcibly expelling the fluid. The centrifugal or jet compressors depend for compression on the kinetic or velocity energy imparted to the fluid.

The *reciprocating compressor* is suited to the compression of relatively small volumes of fluid through a high-pressure range. The *rotary compressor* is suited to the movement of moderate fluid volumes through moderate pressure ranges. The *centrifugal compressor* is suited to the movement of large volumes of fluid through small pressure ranges. Ammonia, carbon dioxide, Freon-12, methyl chloride, and sulfur dioxide are almost always used with reciprocating compressors. Freon-21 is used with rotary compressors, while Freon-11, methylene chloride, and water are used with centrifugal compressors.

Refrigerants. The refrigerants which are used commonly enough to merit classification by the National Board of Fire Underwriters are listed in Table 21-12. The Freon group is now among the most widely used of all refrigerants. These halogenated hydrocarbons are chiefly derived from methane (CH_4) by the replacement of hydrogen molecules with chlorine and fluorine molecules and include F-11, F-12, and F-22.

Those listed as inflammable or in toxicity classification groups 1 to 4 (mildly to seriously toxic depending on concentration, exposure, etc.) include ammonia, butane, dichloroethylene, ethane, ethyl bromide, ethyl chloride, methyl bromide, methyl chloride, methyl formate, propane, and sulfur dioxide.

Those listed as nonflammable (or practically so) and less toxic than group 4 (nontoxic in normally possible concentrations) include carbon dioxide, dichlorodifluoromethane (F-12), monochlorodifluoromethane (F-22), dichlorotetrafluoromethane (F-114), monofluorotrichloromethane

TABLE 21-12 Comparison of Refrigerants
Refrigerating Data Book

Refrigerants	Displacement cfm per ton	Work, hp per ton	Coefficient- of performance	Pressure of saturated vapor, lb/in ² (abs),* at saturation temperature			
				5°F	40°F	86°F	100°F
1. Anhydrous ammonia (NH_3)	3.44	0.989	4.76	34.27	73.32	169.2	211.9
2. Carbon dioxide (CO_2)	0.96	1.840	2.56	331.9	567.8	1043	
3. Dichlorodifluoromethane (CCl_2F_2)(F-12)	5.81	1.002	4.70	26.51	51.68	107.9	131.6
4. Monochlorodifluoromethane (CHClF_2)(F-22)	3.60	1.011	4.66	43.02	83.72	174.5	212.6
5. Monofluorotrichloromethane (CCl_3F)(F-11)	36.32	0.927	5.09	2.93	7.02	18.30	23.60
6. Methyl chloride (CH_3Cl)	5.95	0.962	4.90	20.80	42.60	95.50	119.0
7. Methylene chloride (CH_2Cl_2)	74.30	0.963	4.90	1.17	3.38	10.60	13.25
8. Sulfur dioxide (SO_2)	9.09	0.968	4.87	11.81	27.10	66.50	84.50
9. Water (H_2O)	476.70	1.125	4.10	...	0.25 [†]	...	1.93 [†]

*To obtain gage pressures, deduct 14.7 lb/in² atmospheric pressure. [1 lb/in² = 6.895 kPa; $t_c = (t_F - 32)/1.8$; 1 ton = 907.2 kg.].

[†]These pressures given in inches of mercury absolute.

Note: Figures are based on standard conditions and dry compression and represent the theoretical performance of the refrigerants for these conditions based on their thermodynamic properties. Figures for carbon dioxide and water are unfavorable under standard conditions, since 86°F condensing temperature is close to the critical temperature of CO_2 and 5°F suction temperature is below the freezing point of water.

(F-11), and methylene chloride (dichloromethane). Water is also used as a refrigerant and is, of course, considered as nontoxic and nonflammable.

Refrigerant Properties. Physical and thermodynamic properties of the nine most commonly used refrigerants and comparison of the performance of these refrigerants with the ideal (Carnot) cycle for standard conditions are listed in Table 21-12.

Ammonia is cheap and easily available; its efficiency is so high that it is the practical standard by which other refrigerants are rated. For these reasons it is widely used for ice manufacture and food processing, for example, ice-cream manufacture, meat packing, cold storage, and brewery refrigeration.

Freon refrigerants, which have satisfactory characteristics with respect to toxicity and flammability as well as stable operation characteristics within the normal range, have largely replaced carbon dioxide for air conditioning, etc., where toxic refrigerants present a public hazard.

Methyl chloride, sulfur dioxide, and Freon refrigerants find broad application in commercial and domestic refrigeration service.

Effect of Operating Conditions on Compressor Capacity and Power Requirement. The capacity of any refrigerating compressor depends on the mass of refrigerant vapor that it can convey from the low- to the high-pressure condition. The power requirement of the compressor depends on the mass of vapor conveyed and the pressure differential between the evaporator and the condenser. For this reason the capacity and power requirement of any given compressor operating at constant displacement vary widely depending on the temperature and pressure conditions of the suction and discharge vapor.

It should be noted that although the unit power requirement is much greater for low suction temperatures, the capacity of a constant-displacement machine is greatly reduced owing to reduced density of the vapor and reduced volumetric efficiency, so that the gross power requirement may be far below that at higher suction temperatures. For this reason it is general practice to operate belt-driven compressors at higher speeds when used at lower suction pressures to obtain greater displacement and capacity within the safe power rating of the machine. Care must be exercised in selecting equipment to be sure that safe power limitations will not be exceeded during start-up periods when abnormally high temperatures may be encountered owing to high refrigerant temperatures. This is a very important consideration in the design of ultra-low-temperature systems, especially those employing multiple compressors in cascade arrangement. Within the normal range of condensing temperatures, the change in vapor density is not so pronounced, and the chief effect of departure above the design condensing temperature is a reduction in the output of the compressor.

Evaporators. The largest classification of evaporators for direct air cooling is surface-cooling coils. For cooling water or brine, simple arrangements of submerged pipe coils or plate surface are sometimes used for small applications, especially where refrigeration storage is desirable. More widely used with reciprocating-compression equipment is the so-called dry-expansion liquid cooler in which refrigerant is expanded into the tube surface within a shell and water passed under forced circulation across the tube surface as directed by baffles. Some larger reciprocating-compressor installations and all large-capacity centrifugal refrigeration systems employ a conventional shell-and-tube surface, with forced circulation of water through the tubes, which are mounted within a pool or evaporating refrigerant within the shell surface.

The majority of such applications employ integrally finned tubing.

Expansion Methods. Two general types of refrigerant expansion are employed: (a) dry expansion and (b) flooded expansion.

In the *dry-expansion system* the refrigerant is introduced into the evaporator through an expansion valve or pressure-reducing valve and makes one pass through the evaporating surface going to the compressor or absorber suction line. Since any liquid refrigerant which leaves the evaporator represents a loss of cooling effect, care is taken to assure only dry gas leaving the evaporator. The constant-pressure valve has been largely supplanted by the thermal-expansion valve, which through the use of the self-contained thermostatic-valve principle controls the flow of refrigerant to give a constant superheat at the outlet of the evaporator regardless of the load. Dry-expansion systems are widely used with expensive refrigerants, since only a minimum refrigerant quantity is required to feed the evaporator properly. The dry-expansion system also permits feeding evaporators from the

top so that any oil carried in the refrigerant will flow through the evaporator and be conveyed back to the compressor.

The flooded-expansion system maintains through float-valve control a constant level of refrigerant in the evaporator. In coil-type evaporators this is accomplished by means of a surge chamber external to the coil, usually located above the top and bottom of the coil. Refrigerant is fed into the surge chamber, which is connected with the top and bottom of the coil and to the suction line. As liquid refrigerant passes up through the evaporator coil, its density is reduced owing to the formation of vapor bubbles, so that the refrigerant circulates rapidly through the coil to the surge chamber, where the gas bubbles are released to the suction line. The major disadvantages of the flooded system are the relatively large refrigerant charge required and the necessity of providing means for oil removal when refrigerants that mix readily with oil are used.

Condensers. The function of the condenser is exactly the reverse of the evaporator, that is, to afford a rapid transfer of heat from the condensing refrigerant to the cooling medium. For this reason there is a great similarity between condensing and evaporating equipment. Air-cooled condensers are frequently used with small compression systems which are located in well-ventilated places and where the difficulty of obtaining water supply and drain connections is not commensurate with the operating economies realized through the use of water cooling. Air-cooled condensers are similar in construction to surface-cooling coils.

Because of the effect that high condensing pressures have upon the economy of operation of refrigeration plants, water-cooled condensers are widely used. It is customary to assume the condensing requirement of the average compression plant to be 15,000 Btu/(ton)(h), of which 12,000 Btu represents the cooling work, and 3000 Btu the energy applied in heat pumping. This amount of heat can be absorbed by 1 gal/min of water rising through 30°F, 2 gal/min through 15°F, or 3 gal/min through 10°F. The design of the condenser and the amount of water required will depend on the available water temperature and the desired condensing temperature and pressure.

Water Conservation. The increased use of tap water for condensing purposes in air-conditioning and refrigeration installations has seriously taxed the *water-supply* and *water-disposal* systems of many cities, with the result that restrictions in the form of increased water rates for condensing purposes, taxes on water disposal, or outright prohibition of the use of water for condensing purposes have been effected by many municipalities. This has resulted in the development of equipment for the conservation of water. The familiar *cooling tower* has been redesigned to meet requirements of downtown buildings as to size and appearance, and the spray pond and atmospheric cooling tower find broader application in the industrial field. With spray ponds and atmospheric towers usually 5 gal/(min) · (ton capacity) is allowed with water temperature entering the condenser at 10°F above the maximum outside wet-bulb temperature. With forced-draft towers usually 3 gal/min · ton will suffice with the same temperature limits.

Thoroughly accepted in this field is the *evaporative condenser*, which consists of an extended-coil condenser over which air is driven by fans and which is continually bathed in a water spray. Efficient condensing effect is obtained by the combined effect of air cooling and evaporation of water by the hot condenser coils. Small sizes for capacities up to 5 tons use propeller fans and direct tap-water connection for spray. Larger sizes (condensers in excess of 250 tons capacity have been built) are quite similar to unit air conditioners and employ centrifugal fans and a recirculating-spray system with a centrifugal pump.

Maintenance difficulties attendant upon the use of either cooling towers or evaporative condensers have resulted in a vast increase in the application of air-cooled condensers for reciprocating refrigeration systems in capacities up to 200 tons and possibly higher. While the use of air-cooled condensers results in a considerable operating-power penalty under maximum temperature condition, the apparatus employed is simple and relatively maintenance-free, factors which frequently justify the power penalty resulting from their use.

Refrigeration Compressors. Three basic types of compressor are used in refrigeration and electric chiller applications: reciprocating, rotary, and centrifugal.

Reciprocating compressors are typically used in applications below 250 tons. Reciprocating compressors are less efficient than other compressor designs, using between 0.75 and 1.0 kW/ton.

The design of reciprocating compressors has been profoundly influenced by development of the production-line internal-combustion engine as offered today for automotive and aircraft service. Multicylinder in-line arrangements of 2 to 8 cylinders are thoroughly accepted, as are V and W arrangements of 4 to 16 cylinders and radial arrangements of 3, 5, and 7 cylinders. Practically all machines are single-acting with enclosed crankcases. With multicylinder design, large capacities are obtainable with good balance and relatively low piston speed, so that it is not unusual for machines of up to 120 tons capacity, with forced-feed lubrication, to operate at speeds as high as 1750 r/min. Speeds below 500 r/min (except with very large machines) are the exception rather than the rule. Capacity variation is obtained by unloading groups of cylinders or by bypass or clearance-pocket arrangements.

The overall application of refrigerated air conditioning to large industrial and commercial buildings requires capacities far beyond the range of the largest ice-making or storage refrigeration installations. These requirements have been met adequately by development in the *centrifugal refrigeration* system, which finds current application in single units from 200 to 1800 tons or over in capacity. Drive motors will vary from a low of 0.85 hp/ton for industrial applications to a high of 1.05 hp/ton for commercial installations.

Rotary compressors are available in a number of different versions, including vane, scroll, and screw designs. Screw compressors are used in applications up to 1200 tons. Rotary-vane compressors are used in a wide range of applications from small residential refrigeration units to large, rugged industrial processing plants.

Scroll compressors are typically used in applications below 15 tons. Scroll compressors have some key operating advantages in terms of efficiency and reliability. Although scroll-compressor designs were developed in the early 1900s, their complicated geometry discouraged mass production and the design was never fully commercialized until the 1970s. Advances in manufacturing techniques have enabled the cost-effective production of scroll compressors. As a result of certain performance and reliability advantages, the use of scroll compressors is increasing. Scroll compressors are typically used in smaller refrigeration units, less than 15 tons. Screw compressors are used over a wide range of system capacities, from 50 to 1200 tons. Versions of screw compressors include single helical screws and double-helical screws. Screw compressors operate between 0.6 and 0.75 kW/ton.

Centrifugal compressors are commonly used in applications as large as 2000 tons and in systems as small as 80 tons. Centrifugal compressors offer many advantages, including high efficiency and good reliability. Centrifugal units operate between 0.55 and 0.8 kW/ton.

The original designs for centrifugal systems employed multistage compressors with shaft seals and operating at speeds from 3500 to 7000 r/min. Standard 4-pole or 6-pole open motors with step-up gears were customarily used for compressor drives. Wound-rotor motors affording 25% speed regulation were frequently employed for capacity control. However, since 1955 design has largely been directed toward hermetic systems in which the drive motor is enclosed in the gas passage with the compressor, and with this arrangement the drive is naturally limited to the use of the squirrel-cage induction motor. Control of compressor capacity is afforded by regulating dampers in the compressor suction connection. Common designs employ either two-stage compressors direct-driven by 2-pole motors at approximately 3500 r/min or single-stage compressors operating at 11,000 r/min or higher and driven through step-up gears by enclosed 2-pole motors. One design employs an external frequency converter providing 300-Hz current for operation of a 2-pole induction motor for direct compressor drive at approximately 17,500 r/min. Centrifugal compressors are still offered without the enclosed motor and with the shaft extended through the compressor housing with a suitable seal; as such they can employ the open-motor or turbine drive. However, the general design and control arrangement of the system is generally the same for either hermetic or open drives for manufacturing standardization. Even with open units induction-motor drives are generally selected, for though motor sizes are large, average experience indicates that even where power-factor penalties are involved, power-factor correction can be obtained more economically by the use of capacitors in connection with induction motors rather than through the use of synchronous motors. Where closed motors are employed for compressor drive, they are cooled either by water jacketing or by an arrangement employing a bypass of refrigerant or refrigerant gas for motor cooling.

Compressor Drives. While conventional open motors and V-belt drives are generally employed for large-capacity, low-speed reciprocating compressors, which are still offered, the bulk of the production of reciprocating equipment is now of the direct-drive design generally employing 4-pole 1750-r/min motors. This design permits an extremely compact arrangement which is well suited to the unit-system combinations now widely offered by the industry.

In both the reciprocating and centrifugal compressor fields there is contention as to whether the use of standard open motors or sealed hermetic arrangements is most acceptable. The use of standard open-motor drives necessitates the shaft seal, which offers some disadvantages. The use of the hermetic arrangement requires careful design of the electrical components and close control of the refrigerant atmosphere, which must be kept absolutely moisture-free if electrical problems are to be avoided. Obviously, if failure occurs, the repair of the hermetic motor is a far more serious problem than the repair of the open motor. On the other hand, if properly designed and installed the fully enclosed motor operates in a controlled atmosphere and may be less likely to give trouble. However, with either arrangement the motor is generally a standard 2-pole or 4-pole induction motor as far as the basic electrical design is concerned.

Reciprocating systems generally employ means of unloading by holding suction valves open to afford capacity control in operation and are similarly arranged to start unloaded. Centrifugal systems employ dampers for capacity control, which are kept closed during the starting cycle so that these units also start unloaded. However, the characteristics of the reciprocating system are such that the starting-torque requirement is fairly high. Accordingly, line start for drive motors is preferred wherever utility-company regulations will permit, and since these units are usually to approximately 125-hp maximum size and are frequently installed in multiple units of smaller capacity, line start is generally permissible. Where reduced voltage starting is required, autotransformer or resistance-type reduced-voltage starters are generally employed, although frequently these may be effective only as a means of reducing inrush, as in many instances full line voltage must be applied before the compressor will actually pick up the load.

Centrifugal refrigeration systems generally represent larger-capacity units than reciprocating systems, with motor sizes ranging from 75 to 2000 hp or occasionally higher. However, their starting-torque requirement is very moderate, and it is entirely practical to place the compressor in satisfactory operation by use of the Y- Δ starting system, in which the compressor drive motor is connected across the 3-phase source in a Y arrangement during the starting interval and switched to the Δ connection when the compressor has reached practically full speed and before the compressor damper is opened, permitting the unit to assume load. With this arrangement the current during the starting period can be limited to approximately 130% of the normal full-load running current, and this arrangement is generally entirely satisfactory to power companies. This starting arrangement is almost universally employed with centrifugal systems except for relatively small units, which may be within a range suitable for line start.

Motor Voltage. All standard equipment is based on the assumption that 60-Hz current is available, although some manufacturers will still list a capacity rating of their units of 60-Hz design when employed on 50-Hz service. All systems involving motors up through 5 hp are generally designed for 230-V 60-Hz 1-phase service, but in sizes 3 hp and above are equally available for 208/220/440-V 60-Hz 3-phase service, which is generally available in most urban areas. Equipment for practically the entire available capacity range is designed for service on 208-V 60-Hz 3-phase current, which is commonly available as urban low-voltage distribution. However, it should be noted that because of the rigorous nature of compressor service it is usually inadvisable to attempt to use 220-V equipment for the compressor drive where only 208 V is supplied. Many feel that good design dictates the use of 200-V motors for such service. For larger commercial or industrial applications which are provided with primary service through independent substations, 440-V 60-Hz 3-phase equipment is generally preferred, as it permits a substantial reduction in wiring cost. Currently a number of systems employ 480/277-V 60-Hz 1-phase 4-wire service, where the higher single-phase voltage may be satisfactorily used for fluorescent-lamp operation. This arrangement affords considerable economy in circuit design but presents complications with respect to the use of standard 115-V 60-Hz 1-phase conventional power or office equipment, for which separate transformers and circuiting must

be provided. In the textile industry extensive use is made of 550-V 60-Hz 3-phase service, and equipment is generally available throughout the entire capacity range for this voltage characteristic. In larger plant operations employing plant primary service at either 2300 or 4160 V, these voltages are frequently used for large compressor drives, and most lines make equipment available for this voltage in the range from 200 to 2000 hp, although economics would generally indicate 500-hp drives as being the lowest acceptable size for this voltage.

Reverse-Cycle or Heat Pump. The reverse-refrigeration cycle is for the purpose of heating interiors with electricity. Heat absorbed at a low-temperature level is pumped to a level sufficient to permit satisfactory heating with the expenditure of only the amount of energy necessary to perform the pumping work, which is also reclaimed at the high-temperature level. Under certain circumstances this cycle is entirely practical. Many installations have been made where well water at moderate temperatures ($\pm 50^{\circ}\text{F}$) is available as a low-temperature heat source, and these installations have shown coefficients of performance up to 400%, that is, 5 Btu of heating effect for 1 Btu of energy applied. However, the performance of the refrigeration machine is sharply limited as the temperature head between the evaporator and the condenser is increased, so that the practical possibilities of this cycle are affected not only by the cost of electrical energy compared with other fuels but by the level of the low-temperature heat source and the temperature that must be maintained within the interior.

Application of air conditioning to residences has accelerated activity in the heat-pump field. Since the basic refrigeration equipment is being installed for summer conditioning, its utility is increased by arranging it to handle at least a part of the winter heating requirements. Most new developments are directed toward the use of outside air as a low-temperature heat source as well as a means for providing condensing effect when the system is on the cooling cycle. Heating capacity of such a system will drop fairly rapidly as outside temperatures drop. However, there is a balance point between the requirement for summer cooling and available capacity for winter heating which will permit a rationally designed apparatus to care for the full heating requirements on the reverse-cycle basis for substantial periods during the heating season. Naturally, the more temperate the climate in which the apparatus is employed, the greater proportion of the total winter heat requirement can be handled entirely by the heat-pump principle. Since peak heating demand is experienced only for short periods, usually during early morning hours, the current procedure is to supplement the available output of the heat-pump device by direct resistance heating. This represents a substantial spot load, but its period of use is relatively short, and under most utility rate schedules the overall economies of the operation are reasonable. However, it presents problems in power distribution. A moderate-sized residence in the South Atlantic area with a basic 6-kW requirement for summer or heat-pump operation may be supplemented with as much as 12 kW of additional resistance heating load for use during peak heating periods. This imposes a maximum load of up to 18 kW per residential unit on the lines of the utility, with little possible diversity.

On the other hand, this load occurs at a time when other urban loads are at a minimum and when outside ambient-temperature conditions are at a very low level, so that distribution circuits, transformers, etc., can handle a substantial overload with no difficulty. Accordingly, utility companies are finding that they can handle this load with no serious problems and feel that it is attractive.

A number of ingenious arrangements employing the heat-pump principle or other heat-recovery systems have been incorporated in designs of installations for large commercial buildings. It is evident that the core sections of these buildings are subject to cooling requirements throughout the entire year, as they are shielded from exterior exposure, but subject to heat gains from lighting and occupancy. A number of systems have been employed which use refrigeration for these interior zones throughout the entire year but during the wintertime take the effluent heat from the condenser of the refrigeration system and apply this as a means of heating the periphery of the building which is subject to normal winter exposure. Thus, in effect, the excess heat from the interior core of the building is transferred to the exterior for heating purposes while affording control of the heat load within the core of the building.

Other arrangements provide for direct cooling of lighting equipment either by circulating water or by exhaust ventilation and transfer the heat thus directly recovered to the periphery of the building for heating purposes. There are obviously many possibilities of this nature which must be studied for

each individual project. However, where this means of heating is used, it is dependent on a continued supply of electrical energy to the space as a primary heat source. In some instances arrangement is made to turn on interior lighting during cold periods for the purpose of heating the premises, or where lights are turned off, the equivalent amount of electrical energy may be applied through resistance heating, thus affording a heat source with no increase in electrical demand. These arrangements frequently make full electric heating entirely practical and economical for many large buildings.

Refrigeration Storage: Moderate Temperature. Many refrigeration applications having high peak loads for short periods of time can be most economically handled by the use of relatively small refrigeration machines which are operated over long periods of time to store refrigeration effect to meet the high short-period requirement. Refrigeration effect may be stored in bodies of brine or water, though a relatively large storage volume will be required, since the water or brine can only absorb or give up its sensible heat. A more efficient storage method involves the formation of ice on submerged evaporating coils. Every pound of ice thus formed absorbs and can release, on melting at 32°F, its latent heat of fusion, 144 Btu/lb.

This principle has been frequently used to improve the load factor of refrigeration systems used in conjunction with air-conditioning systems having relatively short use periods (restaurants serving only one meal a day, theaters with only evening showings, and churches or infrequently used auditoriums).

Refrigeration Storage: Low Temperature. A solution of water and salt (or, in general, of any two substances) has a certain concentration which results in the lowest freezing temperature. A solution of this concentration is known as a *eutectic mixture*. A brine with a salt content lower than this concentration will start to freeze above this minimum temperature, and as cooling progresses, pure ice crystals will freeze out, thus increasing the concentration of the brine until the eutectic concentration is reached. At this point freezing will take place at a constant temperature until all latent heat is removed, the resulting crystals being a mechanical mixture of salt and frozen water. If the starting salt concentration of the mixture is greater than the eutectic concentration, salt crystals will first freeze out until the eutectic concentration is reached.

The use of eutectic mixture as a means of storing refrigerating effect, that is, latent heat of fusion, at a temperature below 32°F (the freezing point of water ice) has received wide attention. The eutectic mixture of water 76.7% and sodium chloride (common salt) 23.3% has a freezing temperature of -6°F, and a latent heat of fusion of 101.5 Btu/lb is available at this temperature. Plate evaporators charged with eutectic mixtures are frequently used in refrigerator trucks which are cooled at night to produce sufficient stored cooling effect to meet the next day's operation.

BIBLIOGRAPHY

Sources of additional information on the use of electricity in agriculture are as follows:

Agricultural experiment stations and cooperative extension services, state colleges.

Farm Electrification Section, Agricultural Research Service, U.S. Department of Agriculture (USDA), Beltsville, Md.

National Rural Electric Cooperative Association, 1800 Massachusetts Avenue N.W., Washington, D.C. 20036.

Richey, C. B., Jacobson, P., and Hall C. W., *Agricultural Engineers' Handbook*; New York, McGraw-Hill Book Company, 1961.

Rural Utilities Services, USDA, Washington, D.C.

